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ASSESSMENT OF THE PACIFIC SARDINE
(*Sardinops sagax caerulea*)
POPULATION FOR U.S. MANAGEMENT IN 2006

Kevin T. Hill
Nancy C.H. Lo
Beverly J. Macewicz
Roberto Felix-Uraga

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U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Marine Fisheries Service
Southwest Fisheries Science Center

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(*Sardinops sagax caerulea*)
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Kevin T. Hill¹, Nancy C.H. Lo¹, Beverly J. Macewicz¹, and Roberto Felix-Uraga²

¹NOAA, National Marine Fisheries Service
Southwest Fisheries Science Center
8604 La Jolla Shores Drive
La Jolla, California, USA 92037

²CICIMAR-IPN
Ave. IPN s/n A.P. 592
Col. Playa Palo Sta. Rita C.P. 230096
La Paz, Baja California Sur, Mexico

NOAA-TM-NMFS-SWFSC-386

U.S. DEPARTMENT OF COMMERCE

Carlos M. Gutierrez, Secretary

National Oceanic and Atmospheric Administration

VADM Conrad C. Lautenbacher, Jr., Undersecretary for Oceans and Atmosphere

National Marine Fisheries Service

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LIST OF ACRONYMS AND ABBREVIATIONS

ADMB	automatic differentiation model builder (a programming language)
ASAP	age structured assessment program
BC	British Columbia, Canada
CA	State of California
CANSAR-TAM	catch-at-age analysis for sardine – two area model
CalCOFI	California Cooperative Oceanic Fisheries Investigations
CDFG	California Department of Fish and Game
CDFO	Canada Department of Fisheries and Oceans
CICIMAR-IPN	Centro Interdisciplinario de Ciencias Marinas - Instituto Politécnico Nacional
CONAPESCA	Comisión Nacional de Acuacultura y Pesca
CPS	Coastal Pelagic Species
CPSMT	Coastal Pelagic Species Management Team
CPSAS	Coastal Pelagic Species Advisory Subpanel
CV	coefficient of variation
FMP	fishery management plan
HG	harvest guideline
INP-CRIP	Instituto Nacional de la Pesca - Centro Regional de Investigación Pesquera
MSY	maximum sustainable yield
MX	Mexico
MX-Ensenada	Mexican fishery that lands its product in Ensenada, Baja California
NMFS	National Marine Fisheries Service
NOAA Fisheries	National Oceanic and Atmospheric Administration, National Marine Fisheries Service
OR	State of Oregon
PFMC	Pacific Fishery Management Council
SAFE	stock assessment and fishery evaluation
SEMARNAP	Secretaria del Medio Ambiente, Recursos Naturales y Pesca
SSB	spawning stock biomass
SSC	Scientific and Statistical Committee
SST	sea surface temperature
STAR	Stock Assessment Review (Panel)
STAT	Stock Assessment Team
VPA	virtual population analysis
WA	State of Washington

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EXECUTIVE SUMMARY

A Pacific sardine stock assessment is conducted annually in support of the Pacific Fishery Management Council (PFMC) process that, in part, establishes an annual harvest guideline (quota) for the U.S. fishery. In June 2004, the PFMC, in conjunction with NOAA Fisheries, organized a Stock Assessment Review (STAR) Panel in La Jolla, California, to provide peer review of the methods used for assessment of Pacific sardine and Pacific mackerel. The following report was initially prepared in draft form for the STAR panel's consideration, and was updated for the 2005 management cycle (Conser et al. 2004). Many of the STAR panel review recommendations as well as considerable new data were incorporated into that stock assessment update. The assessment is updated herein for 2006 management; as such, it was reviewed by the Pacific Fishery Management Council (PFMC) and its advisory bodies, and the results were adopted by the PFMC for setting the U.S. harvest guideline in 2006.

This assessment was conducted using 'ASAP', a forward simulation, likelihood-based, age-structured model developed in AD Model Builder. New information has been incorporated into the update, including: (1) new landings data from the Ensenada fishery for the period January 2000 through June 2005; (2) an additional year of landings and biological data from the California and Pacific Northwest fisheries; (3) a DEPM-based estimate of SSB based on the April 2005 survey off California; (4) addition of enhanced aerial spotter survey data from the Southern California Bight, which have been used to recalculate this time series of relative abundance through 2004-05.

Results from the final base model indicate a decline in stock productivity (recruits per spawning biomass) which began in the mid-1990s. Recruit (age-0) abundance increased rapidly from low levels in 1982-83, peaking at 9.5 billion fish in 1994-95. Recruitment has subsequently declined to between 3.5 and 6.5 billion fish per year since that time, with the exception of a strong 2003 year class (YC). Recruit abundance is poorly estimated for the most recent years, however, the 2003 year class YC was estimated to be 10 billion fish. There was a large proportion of 2003 YC in the catch, as well as relatively high abundance in fishery-independent trawl surveys off California and the Pacific northwest. Stock biomass (ages 1+) peaked at 1.48 million metric tons (mmt) in 1996-97, declining to 0.81 mmt in 2003-04. As of July 2005, stock biomass was estimated to be 1.06 mmt.

The primary motivation for conducting this annual assessment is to provide the scientific basis for the Pacific Fishery Management Council's (PFMC) sardine management process. This process -- centered on an environmentally-based control rule -- establishes U.S. coast-wide harvest guidelines (HG) for sardine for the fishing year beginning on January 1st of each year. Based on the sardine biomass estimate from this assessment (1,061,391 mt) and current environmental conditions, the PFMC control rule suggests a 2006 HG for U.S. fisheries of 118,937 mt. This HG recommendation is 13% lower than the HG adopted for calendar year 2005, but 22,049 mt higher than the largest recent harvest by the U.S.

INTRODUCTION

For stock assessment purposes, many of the world's fisheries may be considered data-limited. However, when a data-limited fishery is economically important, data availability generally improves over time as additional resources are allocated to better assess and manage the stock(s). With sufficient time and resources, these data-limited fisheries tend to become data-rich.

In the case of Pacific sardine off the west coast of North America, the fishery has been economically important since the early part of the 20th century. As large scale fishing operations developed, fisheries data collection programs were established along with biological studies and eventually fisheries independent surveys. The fishery collapsed in the 1950's following dramatic declines in stock biomass and remained at low levels for nearly forty years. Sampling programs remained in place, however, and when the stock began to recover in the late 1980's, an apparent data-rich assessment environment appeared to be in place. But sardine biology and ecology, along with oceanographic changes in the Pacific Ocean, conspired to prove this wrong.

For nearly half a century (mid-1940's through mid-1990's), the sardine population was distributed only from Baja California, Mexico northward to Monterey, California USA. This area represented a substantial contraction of the range occupied by sardine when the stock was at high biomass levels (1930's). Fisheries sampling programs were in place over this reduced geographic range; and annual egg production surveys were established in the early 1980's (Wolf 1988a,b), covering sardine spawning areas in southern and central California. Periodic stock assessments took advantage of this data-rich environment. In the mid-1990's, however, the population began a rapid recovery with concomitant expansion of its range northward through British Columbia, Canada. With some lag, fisheries sampling programs were established in the Pacific Northwest but due to budgetary constraints and logistical difficulties, systematic surveys were only recently launched in this area. Consequently, stock assessments are now much more difficult to carry out due to what has become a data-limited situation.

Recently-used Pacific sardine stock assessment models were designed for the data-rich environment and subsequently, had been modified in order to function in the new data-limited environment (Hill et al. 1999). The primary thrust of this paper is go back to basics by examining stock assessment methods that may be better suited from the ground up for contemporary sardine stock assessment and management; and for serving as a flexible framework to take advantage of new data sources as they become available. With regard to the latter, there is a reasonable expectation that over the course of the next few years, there will be significant improvements in the fisheries database, new fisheries-independent surveys, and better understanding of stock structure and the oceanographic constraints that govern suitable sardine habitat and productivity.

BACKGROUND

Scientific Name, Distribution, Stock Structure, Management Units

Biological information about Pacific sardine (*Sardinops sagax caerulea*) is available in Clark and Marr (1955), Ahlstrom (1960), Murphy (1966), MacCall (1979), Leet et al. (2001) and in the

references cited below. Other common names for Pacific sardine include ‘California pilchard’, ‘pilchard’ (in Canada), and ‘sardina monterrey’ (in Mexico).

Sardines, as a group of species, are small pelagic schooling fish that inhabit coastal subtropical and temperate waters. The genus *Sardinops* is found in eastern boundary currents of the Atlantic and Pacific, and in western boundary currents of the Indo-Pacific oceans. Recent studies indicate that sardines in the Alguhas, Benguela, California, Kuroshio, and Peru currents, and off New Zealand and Australia are a single species (*Sardinops sagax*, Parrish et al. 1989), but stocks in different areas of the globe may be different at the subspecies level (Bowen and Grant 1997).

Pacific sardine have at times been the most abundant fish species in the California Current. When the population is large it is abundant from the tip of Baja California (23° N latitude) to southeastern Alaska (57° N latitude), and throughout the Gulf of California. In the northern portion of the range, occurrence tends to be seasonal. When sardine abundance is low, as during the 1960s and 1970s, sardine do not occur in commercial quantities north of Point Conception.

It is generally accepted that sardine off the West Coast of North America consists of three subpopulations or stocks. A northern subpopulation (northern Baja California to Alaska), a southern subpopulation (off Baja California), and a Gulf of California subpopulation were distinguished on the basis of serological techniques (Vrooman 1964) and, more recently, a study of temperature-at capture (Felix-Uraga et al., 2004; 2005). A recent electrophoretic study (Hedgecock et al. 1989) showed, however, no genetic variation among sardine from central and southern California, the Pacific coast of Baja California, or the Gulf of California. A fourth, far northern subpopulation, has also been postulated (Radovich 1982). Although the ranges of the northern and southern subpopulations overlap, the stocks may move north and south at similar times and not overlap significantly. The northern stock is exploited by U.S. fisheries and is included in the Coast Pelagic Species Fishery Management Plan (CPS-FMP; PFMC 1998).

Pacific sardine probably migrated extensively during historical periods when abundance was high, moving north as far as British Columbia in the summer and returning to southern California and northern Baja California in the fall. Tagging studies (Clark and Janssen 1945) indicate that the older and larger fish moved farther north. Migratory patterns were probably complex, and the timing and extent of movement were affected by oceanographic conditions (Hart 1973) and stock biomass. During the 1950s to 1970s, a period of reduced stock size and unfavorably cold sea surface temperatures apparently caused the stock to abandon the northern portion of its range. At present, the combination of increased stock size and warmer sea surface temperatures have resulted in the stock reoccupying areas off northern California, Oregon, Washington, and British Columbia, as well as habitat far offshore from California. During a cooperative U.S.-U.S.S.R. research cruise for jack mackerel in 1991, several tons of sardine were collected 300 nm west of the Southern California Bight (Macewicz and Abramenkoff 1993). Abandonment and re-colonization of the higher latitude portion of their range has been associated with changes in abundance of sardine populations around the world (Parrish et al. 1989).

Important Features of Life History that Affect Management

Life History

Pacific sardine may reach 41 cm, but are seldom longer than 30 cm. They may live as long as 14 years, but individuals in historical and current California commercial catches are usually younger than five years. In contrast, the most common ages in the historical Canadian sardine fishery were six years to eight years. There is a good deal of regional variation in size-at-age, with size increasing from south to north and from inshore to offshore (Phillips 1948, Hill 1999). Size- and age-at-maturity may decline with a decrease in biomass, but latitude and temperature are likely also important (Butler 1987). At low biomass levels, sardine appear to be fully mature at age one, whereas at high biomass levels only some of the two-year-olds are mature (MacCall 1979).

Age-specific mortality estimates are available for the entire suite of life history stages (Butler et al. 1993). Mortality is high at the egg and yolk sac larvae stages (instantaneous rates in excess of 0.66 d^{-1}). Adult natural mortality rates has been estimated to be $M=0.4 \text{ yr}^{-1}$ (Murphy 1966; MacCall 1979) and 0.51 yr^{-1} (Clark and Marr 1955). A natural mortality rate of $M=0.4 \text{ yr}^{-1}$ means that 33% of the sardine stock would die each year of natural causes if there were no fishery.

Pacific sardine spawn in loosely aggregated schools in the upper 50 meters of the water column. Spawning occurs year-round in the southern stock and peaks April through August between San Francisco and Magdalena Bay, and January through April in the Gulf of California (Allen et al. 1990). Off California, sardine eggs are most abundant at sea surface temperatures of 13°C to 15°C and larvae are most abundant at 13°C to 16°C . Temperature requirements are apparently flexible, however, because eggs are most common at 22°C to 25°C in the Gulf of California and at 17°C to 21°C off Central and Southern Baja (Lluch-Belda et al. 1991).

The spatial and seasonal distribution of spawning is influenced by temperature. During periods of warm water, the center of sardine spawning shifts northward and spawning extends over a longer period of time (Butler 1987; Ahlstrom 1960). Recent spawning has been concentrated in the region offshore and north of Point Conception (Lo et al. 1996). Historically, spawning may also have been fairly regular off central California. Spawning was observed off Oregon (Bentley et al. 1996), and young fish were seen in waters off British Columbia in the early fishery (Ahlstrom 1960) and during recent years (Hargreaves et al. 1994). The main spawning area for the historical population off the U.S. was between Point Conception and San Diego, California, out to about 100 miles offshore, with evidence of spawning as far as 250 miles offshore (Hart 1973).

Sardine are oviparous multiple-batch spawners with annual fecundity that is indeterminate and highly age- or size-dependent (Macewicz et al. 1996). Butler et al. (1993) estimated that two-year-old sardine spawn on average six times per year whereas the oldest sardine spawn up to 40 times per year. Both eggs and larvae are found near the surface. Sardine eggs are spheroid, have a large perivitelline space, and require about three days to hatching at 15°C .

Sardine are planktivores that consume both phytoplankton and zooplankton. When biomass is high, Pacific sardine may consume a significant proportion of total organic production in the

California Current system. Based on an energy budget for sardine developed from laboratory experiments and estimates of primary and secondary production in the California Current, Lasker (1970) estimated that annual energy requirements of the sardine population would have been about 22% of the annual primary production and 220% of the secondary production during 1932 to 1934, a period of high sardine abundance.

Pacific sardine are taken by a variety of predators throughout all life stages. Sardine eggs and larvae are consumed by an assortment of invertebrate and vertebrate planktivores. Although it has not been demonstrated in the field, anchovy predation on sardine eggs and larvae was postulated as a possible mechanism for increased larval sardine mortality from 1951 through 1967 (Butler 1987). There have been few studies about sardine as forage, but juvenile and adult sardine are consumed by a variety of predators, including commercially important fish (e.g., yellowtail, barracuda, bonito, tuna, marlin, mackerel, hake, salmon, and sharks), seabirds (pelicans, gulls, and cormorants), and marine mammals (sea lions, seals, porpoises, and whales). In all probability, sardine are consumed by the same predators (including endangered species) that utilize anchovy. It is also likely that sardine will become more important as prey as their numbers increase. For example, while sardine were abundant during the 1930s, they were a major forage species for both coho and chinook salmon off Washington (Chapman 1936).

Abundance, Recruitment, and Population Dynamics

Extreme natural variability and susceptibility to recruitment overfishing are characteristic of clupeoid stocks like Pacific sardine (Cushing 1971). Estimates of the abundance of sardine from 1780 through 1970 have been derived from the deposition of fish scales in sediment cores from the Santa Barbara basin off southern California (Soutar and Isaacs 1969, 1974; Baumgartner et al. 1992). Significant sardine populations existed throughout the period with biomass levels varying widely. Both sardine and anchovy populations tend to vary over periods of roughly 60 years, although sardine have varied more than anchovy. Sardine population declines were characterized as lasting an average of 36 years; recoveries lasted an average of 30 years. Biomass estimates of the sardine population inferred from scale-deposition rates in the 19th and 20th centuries (Soutar and Isaacs 1969; Smith 1978) indicate that the biomass peaked in 1925 at about six million mt.

Sardine age-three and older were fully recruited to the historical fishery until 1953 (MacCall 1979). Recent fishery data indicate that sardine begin to recruit at age zero and are fully recruited to the southern California fishery by age two. Age-dependent availability to the fishery likely depends upon the location of the fishery; young fish are unlikely to be fully available to fisheries located in the north and old fish are unlikely to be fully available to fisheries south of Point Conception.

Sardine spawning biomass estimated from catch-at-age analysis averaged 3.5 million mt from 1932 through 1934, fluctuated between 1.2 million mt to 2.8 million mt over the next ten years, then declined steeply during 1945 through 1965, with some short-term reversals following periods of particularly successful recruitment (Murphy 1966; MacCall 1979). During the 1960s and 1970s, spawning biomass levels were thought to be less than about five thousand to ten thousand mt (Barnes et al. 1992). The sardine stock began to increase by an average rate of 27% annually in the early 1980s (Barnes et al. 1992). Recent estimates (Hill et al. 1999; Conser et al.

2004) indicate that the total biomass of sardine age one or older is greater than one million metric tons.

Recruitment success in sardine is generally autocorrelated and affected by environmental processes occurring on long (decadal) time scales. Lluch-Belda et al. (1991) and Jacobson and MacCall (1995) demonstrated relationships between recruitment success in Pacific sardine and sea surface temperatures measured over relatively long periods (i.e., three years to five years). Their results suggest that equilibrium spawning biomass and potential sustained yield is highly dependent upon environmental conditions associated with elevated sea surface temperature conditions.

Recruitment of Pacific sardine is highly variable. Analyses of the sardine stock recruitment relationship have been controversial, with some studies showing a density-dependent relationship (production of young sardine declines at high levels of spawning biomass) and others finding no relationship (Clark and Marr 1955; Murphy 1966; MacCall 1979). The most recent study (Jacobson and MacCall 1995) found both density-dependent and environmental factors to be important.

MacCall (1979) estimated that the average potential population growth rate of sardine was 8.5% during the historical fishery while the population was declining. He concluded that, even with no fishing mortality, the population on average was capable of little more than replacement. Jacobson and MacCall (1995) obtained similar results for cold, unproductive regimes, but also found that the stock was very productive during warmer regimes.

MSY for the historical Pacific sardine population was estimated to be 250,000 mt annually (MacCall 1979; Clark 1939), which is far below the catch of sardine during the peak of the historical fishery. Jacobson and MacCall (1995) found that MSY for sardine depends on environmental conditions, and developed a stock-recruitment model that incorporates a running average of sea-surface temperature measured off La Jolla, California. This stock-recruitment model has been used in recent assessments.

Relevant History of the Fishery

The sardine fishery was first developed in response to demand for food during World War I. Landings increased from 1916 to 1936, and peaked at over 700,000 mt. Pacific sardine supported the largest fishery in the western hemisphere during the 1930s and 1940s, with landings along the coast in British Columbia, Washington, Oregon, California, and Mexico. The fishery declined, beginning in the late 1940s and with some short-term reversals, to extremely low levels in the 1970s. There was a southward shift in the catch as the fishery decreased, with landings ceasing in the northwest in 1947 through 1948, and in San Francisco in 1951 through 1952. Sardine were primarily used for reduction to fish meal, oil, and as canned food, with small quantities taken for live bait. An extremely lucrative dead bait market developed in central California in the 1960s.

In the early 1980s, sardine fishers began to take sardine incidentally with Pacific (chub) mackerel and jack mackerel in the southern California mackerel fishery. Sardine were primarily

canned for pet food, although some were canned for human consumption. As sardine continued to increase in abundance, a directed purse-seine fishery was reestablished. Sardine landed in the directed sardine U.S. fisheries are mostly frozen and sold overseas as bait and aquaculture feed, with minor amounts canned or sold fresh for human consumption and animal food. Small quantities are harvested live bait.

Besides San Pedro and Monterey, California, significant Pacific sardine landings are now made in the Pacific northwest and in Baja California, Mexico. Sardine landed in Mexico are used for reduction, canning, and frozen bait. Total annual harvest of Pacific sardine by the Mexican fishery is not regulated by quotas, but there is a minimum legal size limit of 165 mm. To date, no international management agreements between the U.S. and Mexico have been developed.

Management History

The sardine fishery developed in response to an increased demand for protein products that arose during World War I. The fishery developed rapidly and became so large that by the 1930s sardines accounted for almost 25% of all fish landed in the U.S. (Leet et al. 2001). Coast wide landings exceeded 350,000 mt each season from 1933 through 1934 to 1945 through 1946; 83% to 99% of these landings were made in California, the remainder in British Columbia, Washington, and Oregon. Sardine landings peaked at over 700,000 tons in 1936. In the early 1930s, the State of California implemented management measures including control of tonnage for reduction, case pack requirements, and season restrictions.

In the late 1940s, sardine abundance and landings declined dramatically (MacCall 1979; Radovich 1982). The decline has been attributed to a combination of overfishing and environmental conditions, although the relative importance of the two factors is still open to debate (Clark and Marr 1955; Jacobson and MacCall 1995). Reduced abundance was accompanied by a southward shift in the range of the resource and landings (Radovich 1982). As a result, harvests ceased completely in British Columbia, Washington, and Oregon in the late 1940s, but significant amounts continued to be landed in California through the 1950s.

During 1967, in response to low sardine biomass, the California legislature imposed a two-year moratorium that eliminated directed fishing for sardine, and limited the take to 15% by weight in mixed loads (primarily jack mackerel, Pacific [chub] mackerel and sardines); incidentally-taken sardines could be used for dead bait. In 1969, the legislature modified the moratorium by limiting dead bait usage to 227 mt (250 short tons). From 1967 to 1974, a lucrative fishery developed that supplied dead bait to striped bass anglers in the San Francisco Bay-Delta area. Sardine biomass remained at low levels and, in 1974, legislation was passed to permit incidentally-taken sardines to be used only for canning or reduction. The law also included a recovery plan for the sardine population, allowing a 907 mt (1,000-short ton) directed quota only when the spawning population reached 18,144 mt (20,000 short tons), with increases as the spawning stock increased further.

Management Since Onset of the Recovery

In the late 1970s and early 1980s, CDFG began receiving anecdotal reports about the sighting,

setting, and dumping of "pure" schools of juvenile sardines, and the incidental occurrence of sardines in other fisheries, suggesting increased abundance. In 1986, the state lifted its 18-year moratorium on sardine harvest on the basis of sea-survey and other data indicating that the spawning biomass had exceeded 18,144 mt (20,000 short tons). CDFG Code allowed for a directed fishery of at least 907 mt once the spawning population had returned to this level. California's annual directed quota was set at 907 mt (1,000 short tons) during 1986 to 1990; increased to 10,886 mt in 1991, 18,597 mt in 1992, 18,144 mt in 1993, 9,072 mt in 1994, 47,305 mt in 1995, 34,791 mt in 1996, 48,988 mt in 1997, 43,545 mt in 1998, and 120,474 mt in 1999.

Management Under the PFMC CPS Fishery Management Plan (2000 to Present)

In January 2000, management authority for the U.S. Pacific sardine fishery was transferred to the Pacific Fishery Management Council. Pacific sardine was one of five species included in the federal CPS-FMP (PFMC 1998). The CPS-FMP includes a maximum sustainable yield (MSY) control rule intended to prevent Pacific sardine from being overfished and maintain relatively high and consistent catch levels over a long-term horizon. The harvest formula for sardine is provided at the end of this report (see '**Harvest Guideline for 2006**' below). A thorough description of PFMC management actions for sardine, including harvest guidelines, may be found in the most recent CPS SAFE document (PFMC 2005). U.S. harvest guidelines and resultant landings are displayed in Figure 1.

ASSESSMENT DATA

Biological Parameters

Stock Structure

For purposes of this assessment, we assume a single Pacific sardine stock that extends from northern Baja California, Mexico to British Columbia, Canada and extends well offshore, perhaps 300 nm or more (Macewicz and Abramenkoff 1993; Hill et al. 1999). More specifically, all U.S. and Canadian landings are assumed to be taken from the single stock being accessed. Similarly, all sardine landed in Ensenada, Baja California, Mexico are also assumed to be taken from the single stock being accessed and sardine landed in Mexican ports south of Ensenada are considered to be part of another stock that may extend from southern Baja California into the Gulf of California. In the near future, alternative stock structure scenarios will be explored, including one that separates the catches in Ensenada and San Pedro into the 'cold' and 'temperate' stocks proposed by Felix-Uraga et al. (2004, 2005) and takes into account subpopulation differences in growth and natural mortality.

Length-weight Relationship

The length-weight relationship for Pacific sardine was modeled using fish measured from survey and port samples collected from 1982 to 2004. The following power function was used to determine the relationship between weight (g) and standard length (mm) for both sexes combined:

$$W_L = a (L^b),$$

where W_L is weight-at-length L , and a and b are the estimated regression coefficients. The estimated coefficients were $a = 0.000001$ and $b = 3.113$ (corrected $R^2 = 0.928$; $n = 86,606$).

Length-at-age Relationship

The von Bertalanffy growth equation was used to derive the relationship between standard length (mm) and age (yr) for Pacific sardine:

$$L_A = L_\infty (1 - e^{-K(A-t_0)}),$$

where L_A is the length-at-age A , L_∞ ('L infinity') is the theoretical maximum size (length) of the fish, K is the growth coefficient, and t_0 ('t zero') is the theoretical age at which the fish would have been zero length. The best estimate of von Bertalanffy parameters for Pacific sardine was: $L_\infty = 244$ mm, $K = 0.319$, and $t_0 = -2.503$ (corrected $R^2 = 0.561$; $n = 86,606$).

Maximum Age and Size

The largest recorded Pacific sardine was 410 mm long (Eschmeyer et al. 1983), but the largest Pacific sardine taken by commercial fishing since 1983 was 288 mm and 323 g. The oldest recorded age for a Pacific sardine was 14 years, but most commercially-caught sardine are typically less than four years old.

Maturity Schedule

The maturity schedule provided in Table 1 was used for all model runs (Hill et al. 1999). The "Coded Age" appears in all model input and output files. The correspondence between "Coded Age" and "True Age" is also provided in the table.

Natural Mortality

Adult natural mortality rates have been estimated to be $M=0.4 \text{ yr}^{-1}$ (Murphy 1966; MacCall 1979) and 0.51 yr^{-1} (Clark and Marr 1955). A natural mortality rate of $M=0.4 \text{ yr}^{-1}$ means that 33% of the sardine stock would die each year of natural causes if there were no fishery. Consistent with previous assessments, the instantaneous rate of natural mortality was taken as 0.4 yr^{-1} for all ages and years (Murphy 1966, Deriso et al. 1996, Hill et al. 1999).

Fishery Data

Overview

Fishery data for assessing Pacific sardine include commercial landings and port sample (biological) data for three regional fisheries: California (San Pedro and Monterey), northern Baja California (Ensenada), and the Pacific northwest (Oregon, Washington, and British Columbia). Biological data includes individual weight (g), standard length (mm), sex, maturity, and otoliths for age determination. CDFG currently collects 12 random port samples (25 fish per sample) per month to determine age composition and weights-at-age for the directed fishery. Mexican port samples, collected by INP-Ensenada since 1989, were aged and made available for this assessment by coauthor Felix-Uraga. ODFW and WDFW have collected port samples since 1999. A listing of sample sizes relative to fishery landings, 1982-83 to present, is provided in Table 2.

Following recommendations of the CPS STAR Panel (PFMC 2004), all fishery inputs were compiled based on a ‘biological year’ as opposed to a calendar year time step, with the biological year being based on the birthdates used to assigned age. Therefore, data were aggregated from July 1 (year_x) through June 30 (year_{x+1}). In the input and output files, the sardine fisheries (or ‘Fleets’) are assigned numbers as follows:

<i>ASAP Fleet Number</i>	<i>Corresponding Sardine Fishery</i>
1	California (San Pedro and Monterey)
2	Ensenada (northern Baja California, México)
3	Pacific Northwest (Oregon, Washington, British Columbia)

Landings

The ASAP model includes commercial landings in California, northern Baja California and the Pacific Northwest from 1982-83 through 2005-06. Landings were aggregated by biological year and are presented in Table 2 and Figure 2.

California commercial landings were obtained from a variety of sources based on dealer landing receipts (CDFG), which in some cases augmented with special sampling for mixed load portions. During California’s incidental sardine fishery (1982-83 through 1990-91), many processors reported sardine as mixed with jack or Pacific mackerel, but in some cases sardine were not accurately reported on landing receipts. For these years, sardine landings data were augmented with shore side ‘bucket’ sampling of mixed loads to estimate portions of each species. CDFG reports these data in monthly ‘Wetfish Tables’, which are still distributed by the Department. These tables are considered more accurate than PacFIN or other landing receipt-based statistics for California CPS, so were used for this assessment. Projected landings for 2005-06 were based on real data for July-September 2005, substituting monthly data from 2004-05 (i.e. October-June) for corresponding months in 2005-06.

Ensenada (northern Baja California) landings from July 1982 through December 1999 were compiled using monthly landings from the ‘Boletín Anual’ series published by the Instituto Nacional de la Pesca’s (INP) Ensenada office (e.g. see Garcia and Sánchez, 2003). Monthly catch data from January 2000 through June 2005 were provided by Dr. Tim Baumgartner (CICESE-Ensenada, Pers. Comm.), who obtained the data electronically from Sr. Jesús Garcia Esquivel (Department of Fisheries Promotion and Statistics, SEMARNAP-Ensenada). These new catch data for 2000-2005 incorporate estimates of sardine delivered directly to tuna rearing pens off northern Baja California, and are overall 37% higher than statistics used in the previous assessment. Projected landings for 2005-06 were based on the 2004-05 value.

For the Pacific Northwest fishery, we included sardine landed in Oregon, Washington, and British Columbia. Monthly landing statistics were provided by ODFW (McCrae 2001-2004, McCrae and Smith 2005), WDFW (WDFW 2001, 2002 and 2005; Robinson 2003, Culver and Henry 2004), and CDFO (Christa Hrabok, pers. comm.). Projected landings for 2005-06 were based on real data for July-September 2005, substituting monthly data from 2004-05 (i.e. October-June) for corresponding months in 2005-06.

Catch-at-age

Descriptions of sardine otolith ageing techniques can be found in Walford and Mosher (1943) and Yaremko (1996). Pacific sardine are aged by fishery biologists in Mexico, California, and the Pacific Northwest, using annuli in sagittal otoliths. A birth date of July 1 was assumed when assigning ages to California, Oregon, and Washington samples. Ensenada age assignments were adjusted to match this assumption *post-hoc* by subtracting one year of age from fish caught during the first semester of the calendar year. Sample sizes by fishery and biological year are provided in Table 2.

Catch-at-age matrices were developed for each fishery using port sample and landings data aggregated by month. Estimates of catch-at-age were weighted to take into account variation in sample size relative to total landings. Sample percent-by-weight for each age class was calculated by dividing the total weight of fish-at-age by the total weight of fish sampled in each month. Landed weight of fish in each age class was estimated as the product of metric tons landed and the percent-by-weight in the fishery sample. Numbers-at-age in the monthly landings were then calculated by dividing the landed weight-at-age by the average individual weight-at-age for the month. For months with landings but no fishery sample taken, data were substituted by summing sample information (i.e., fish numbers, weights, and sample weights) from the two adjacent (previous and following) months. Finally, numbers-at-age were summed across months to provide the catch-at-age (thousands of fish) for each biological year. Individuals five years of age and older were pooled into a 'plus' group, and sexes were pooled for the assessment. Catch-at-age data compiled for ASAP input are provided in Tables 3-5, and proportions-at-age are displayed in Figures 3-5. Based on estimates from preliminary model runs, effective sample sizes for the California and Ensenada fisheries were set to $\lambda=50$. Effective sample size for the Pacific Northwest fishery data was estimated to be lower, and was set to $\lambda=12$ for the final base run. In years with landings but no samples, effective sample size was set to zero.

Historical catch-at-age data (1932-65) have been examined for possible use in the modeling. Problems with consistency of the ageing during significant parts of the historical period coupled with the lack of indices of abundance for the period, made these data difficult to use in conjunction with data from the contemporary period (1982 to present). While the historical data were not used formally in the modeling, the historical VPA biomass estimates derived from them were used qualitatively for establishing the scale for virgin SSB estimates in the ASAP modeling of the contemporary period.

Fishery weight at age

Mean weights-at-age were calculated for each fishery and biological year by dividing total sampled weight of fish-at-age by the total number of fish-at-age. The current version of ASAP is only configured to accommodate one weight-at-age matrix, so a pooled weight-at-age was calculated by taking a weighted weight-at-age for the three fisheries, using respective landings in each year as a basis for the weighting. Pooled fishery weights-at-age applied in ASAP are provided in Table 6 and Figure 6.

Population weight at age

Because the sardine fisheries do not cover the stocks' full geographic range (i.e., fishery coverage is generally inshore, whereas the spawning stock extends 200 miles offshore), fishery

weight-at-age estimates are often smaller than those of the population as a whole. For the purposes of converting model-based stock numbers at age estimates into stock biomass (Ages 1+) estimates for management, biological samples from fishery-independent sources that span the geographical range of the stock were used to calculate population weights-at-age (Table 7). Data included survey samples from summer 1998 and spring 2004.

Fishery-Independent Data

Overview

In the input and output files, the fisheries-independent indices of abundance are assigned numbers as follows:

Index Number	Corresponding Data	Represents
1	DEPM	SSB
2	Aerial Spotter	Biomass of Ages 0-2

Daily Egg Production Method (DEPM) Spawning Biomass Index (Index 1)

Daily egg production method (DEPM) biomass estimates were available 1985-2004 with several years missing from the series (Table 8, Figure 7). Lo et al. (1996) and Lo and Macewicz (2004) provide the methodology employed and the sampling constraints. Note in particular that adult samples were not taken on a regular basis and consequently, it was necessary to assume that the adult reproductive parameters were constant for most years in the series. The index was taken to represent sardine SSB in April (month 10) of each biological year. CVs for DEPM estimates are also presented in Table 8. The 2004-05 DEPM estimate, based on eggs and adults collected during the April 2005 survey, was 619,320 mt of SSB (Table 8). The modeled selectivity pattern was set using the maturity-at-age proportions (Table 9, Figure 9). Within ASAP, a CV of 0.30 was applied to all DEPM observations.

Aerial Spotter Survey (Index 2)

Pilots employed by the fishing fleet to locate Pacific sardine (and other pelagic fish) schools report data for each flight on standardized logbooks and provide them under contract to NOAA Fisheries. Spotter indices for sardine have been calculated as year effects estimated using delta log-normal linear models (Lo et al. 1992). The current spotter index covers the period 1985 through 2004, with a July-June time step (Table 8, Figure 7). After the year 2000, there was rapid decline in both the number of active pilots and total logbooks returned, as well as a southward shift in effort to offshore areas off of Baja California. To remedy this problem, NOAA Fisheries contracted professional spotter pilots to survey the Southern California Bight region in 2004 and 2005. Newly available data from this enhanced survey were incorporated into the index, and a new time series was calculated using a Generalized Linear Model (GLM; Table 8).

CVs of GLM estimates were high from 2000-01 onward compared to the earlier part of the time series, partially due to reduced sample sizes in recent years (Table 8, Figure 8). To account for this uncertainty, we applied higher CVs to observed values within ASAP (increasing from 0.3 to 0.7 in the final year; Figure 8), in effect lowering the influence of the 2000-01 to 2004-05 spotter data in the overall likelihood. We applied a CV of 0.30 to all observations prior to 2000-01. The

aerial survey index was taken to represent the inshore, younger sardine (primarily ages 0-2; Table 9, Figure 9).

ASSESSMENT MODEL

ASAP Model Description

Overview

The Age-structured Assessment Program (ASAP) model (Legault and Restrepo 1999; see Appendix I) is based on the AD Model Builder (ADMB) software environment, which is essentially a high-level programming language that utilizes C++ libraries for nonlinear optimization (Otter Research 2001). Further, the ASAP model is maintained through the NOAA Fisheries Toolbox Project (NFT), which includes various fishery-related models that have been customized with graphical user interfaces (GUIs) to enable users to conduct modeling exercises and evaluate results more easily. Further, the ADMB code is provided so that experienced users can make modifications to meet specific needs.

The general estimation approach used in the ASAP is that of a flexible forward-simulation that allows for the efficient and reliable estimation of a large number of parameters. The population dynamics and statistical underpinnings of ASAP are well established and date back to Fournier and Archibald (1982), and Deriso et al. (1985). However, reliable implementation of such large scale models for fisheries stock assessment has only become practical during the past decade as microprocessors have become powerful enough to handle the computational demands and professional quality optimization software (ADMB) has been developed.

The following is a brief description of estimation methods employed in the ASAP model. Readers interested in further details and model equations should refer to Legault and Restrepo (1999; see Appendix I).

- Model estimation begins in the first year of available data with an estimate of the population abundance-at-age.
- The spawning stock for that year is calculated and the associated recruitment for the next year is determined via the stock-recruitment relationship (in this case, based on a Beverton-Holt model). Recruitment variability is accommodated by accounting for divergence from the estimated central tendency (expected value).
- Each cohort estimated in the initial population abundance at age is then reduced by the total mortality rate and subsequently, projected into the next year/age combination. This process of estimating recruitment and projecting the population 'forward' continues until the final year of data is reached.
- Total mortality rates (Z) used to decrease cohort abundances over time represent the sum of natural mortality (M) and the fishing mortalities (F) from all fisheries.
- The F s for each fishery are assumed to be 'separable' into age (commonly referred to as selectivity) and year (commonly referred to as F -multipliers). The product of selectivity-at-age and the year specific F -multiplier equals the F for each fishery/year/age combination.
- The added structure of time-varying selectivity and/or catchability can be incorporated

- via the estimation of random walks.
- Predicted catch in weight and catch-at-age are estimated using Baronov's catch equation and user-provided mean weights at age and natural mortality.
 - The method of maximum likelihood serves as the foundation of the overall numerical estimation. Sources of data are compartmentalized into various likelihood components, depending on the level of structure of the overall, fully-integrated population model. Generally, the ASAP model includes nine likelihood components and a few penalties, given a baseline population model (Table 10).
 - The tuning indices are assumed to represent changes in the population over time for specific age ranges and can be measured in numbers or weight.
 - Given the large number of parameters, it is possible to fit both the catch-at-age and the abundance indices relatively well, but often at the expense of producing somewhat unrealistic trends in other stock parameters of interest (e.g., recruitment, selectivity, and catchability). Constraints and penalty functions can be employed to constrain estimation to more feasible regions of parameter space.
 - Because the number of parameters can be large and highly nonlinear, it is often difficult to estimate all parameters simultaneously in one run of the model. In practice, the minimization usually proceeds in phases, where groups of parameters are estimated simultaneously, while the remaining parameters are maintained at their initially assigned ('starting') values. Once the objective function is minimized for a particular phase, more parameters are evaluated in a step-wise fashion. Estimation within additional phases continues until all parameters are estimated. For this assessment, parameters were estimated in the following order: Phase (1): Selectivity in 1st Year, Fmult in 1st Year, Catchability in 1st Year, Stock-Recruitment Relationship, and Steepness; Phase (2): Fmult Deviations, Recruitment Deviations; Phase (3): Selectivity Deviations.
 - While ASAP has the ability to estimate population numbers at age in the first year, attempts to do so with sardine resulted in unrealistically high numbers in the initial population which carried through the entire time series. For this reason, we fixed numbers-at-age for the initial population to a biomass equivalent of 5,000 mt. Specifically, numbers-at-age (1,000s) for ages 0 to 5+ were set to the following starting values, respectively: 25,000, 15,000, 9,000, 5,400, 3,240, and 1,944.

Assessment Program with Last Revision Date

ASAP version 1.3.2 (compiled 14 Sept. 2004) was used for all runs presented in this paper. ASAP was implemented using NFT GUI version 2.7 (compiled 4 Mar. 2005).

Likelihood Components and Model Parameters

Likelihood components in the final ASAP base model ('Base-D5') are listed in Table 10. Parameterization summaries for the baseline ASAP model are provided in Table 11.

Convergence Criteria

The iterative process for determining numerical solutions in the model was continued until the difference between successive likelihood estimates was <0.0001 . The number of function evaluations ranged from 800 to 10,000, depending on the model configuration and initial values. Fidelity of model convergence was explored by modifying selected initial values (stock size at the beginning of the time series, catchability coefficients associated with indices of abundance,

etc.) and then comparing the likelihoods and estimates of key management parameters.

MODEL RESULTS

Overview

An ASAP model was developed initially by mimicking (to the extent possible) the structure employed in the last CANSAR-TAM stock assessment (Conser et al 2003). However, as noted above, recent assessments have not used the fisheries data from the northern area (OR+WA+BC) – instead fish were moved from the modeled southern area at fixed transfer rates. In this implementation of ASAP, fisheries data from the northern area were fully incorporated and no assumptions were made regarding sardine migration rates. The initial model configuration was then modified following recommendations of the June 2004 STAR Panel and further examination of model diagnostics. This process resulted in the baseline model ‘Base-D5’ described herein.

In the ASAP baseline model, most parameters were freely estimated without strong constraints or penalties. The likelihood components at the optimal solution are provided in Table 10. A total of 136 parameters were estimated (Table 11). Model run times were usually only a few minutes and generally converged without problem, and with a positive-definite Hessian matrix. Limited exploration of the response surface via adjustments to the starting values did not uncover additional local minima. Standard deviations were reasonable for most of the key model parameters including the derived parameters such as SSB (Table 11).

Catch

Model fit to catch data for each fishery is displayed in Figure 11. The observed and predicted time series essentially overlay each other, indicating a precise fit to this data source.

Catch-at-age

Based on estimates from preliminary model runs, effective sample sizes for the California and Ensenada fisheries were set to $\lambda=50$. Effective sample size for the Pacific Northwest fishery data was estimated to be lower, and was set to $\lambda=12$ for the final base run (Figure 12). Model residuals for catch-at-age data are displayed in Figure 13. Residuals for the three fisheries were random, with no obvious trends over age or time.

Indices of Abundance

Model fit to DEPM data is displayed in Figure 14A. Model fit to Aerial Spotter data is displayed in Figure 14B. Comparisons of observed data for the two indices may be found in Figures 10A&B. Note the inverse relation between the two indices for the year-year comparison (Figure 10A), and relative lack of correlation when DEPM is lagged by two years (Figure 10B) to account for differences in selectivity.

Selectivity Estimates

Estimated selectivity (S_{age}) for the three respective fisheries is displayed in Figure 15. Selectivity for the California fishery was estimated for two periods: 1982-1990 (biological years) when the population was smaller, quotas were lower, and a large portion of sardine was captured mixed with schools of jack and Pacific mackerel; and 1991-2005, when the population was larger, quotas were higher, and pure schools of sardine were targeted. Estimated selectivity patterns for the California and Ensenada fisheries were dome-shaped (Figure 15), with 2 year old fish being fully selected. Relative paucity of older ages in these two fisheries is likely an artifact of availability (larger, older fish offshore or north of the fishing grounds) as opposed to gear- or market-related causes. Estimated selectivity for the Pacific Northwest fishery is asymptotic (Figure 15), with the oldest two ages being more or less fully selected. Again, this likely reflects the coast-wide distribution of sardine population.

Fishing Mortality Rate

Fishing mortality estimates for the three respective fisheries are displayed in Figure 16. Combined fishing mortality-at-age is displayed in Figure 17 and Table 12.

Spawning Stock Biomass

Population SSB from the final model is provided in Tables 11 and 13.

Recruitment

Recruitment estimates (age-0 abundance) are presented in Tables 11 and 13 and displayed in Figure 18. The recruitment trend is generally similarly similar to that of Conser et al. (2004), with peaks in 1994-95 (9.46 billion) and 2003-04 (10.04 billion). The trend increases more rapidly and to a slightly higher peak in 1994-95. This change is attributed to the greater magnitude of change in the Aerial Spotter GLM index (selectivity for pre-adults), which was entirely recalculated for the current assessment.

Stock-recruitment Relationship

Recruitment CVs were set at 0.5 for most years in ASAP. Recruits are poorly estimated in the final years of any age-structured model. To obtain more reasonable estimates of recruitment and biomass in recent years, we increased weights on spawner-recruit predictions in ASAP by applying gradually smaller CVs (0.4, 0.3, 0.2, 0.1, 0.05) from 2001 to 2005. A similar S - R constraint has been applied in previous sardine assessments (Deriso et al. 1996, Hill et al. 1999, Conser et al. 2003). The relationship between SSB and recruitment is displayed in Figure 19. Beverton-Holt model parameters for the final model were estimated as follows: $\alpha = 5.226e+06$; $\beta = 172,667$; $\text{Virgin} = 1.258e+06$; and Steepness (h) = 0.67 (Table 11).

Relative spawning success, calculated as anomalies from average $\ln(R/SSB)$, is displayed in Figure 20. Spawning success was highest during the onset of the recovery, with a trend toward negative anomalies in more recent years. Positive anomalies in 1993-94 and 2002-03 are

attributed to peak year classes in 1994 and 2003.

The strong recruitment estimated for 2003 was driven, in part, by large portions of this year class in the California fishery samples in 2003-04 and 2004-05 (Table 3, Figure 3), as well as relatively large proportions of this year class in the Pacific Northwest fishery in 2004-05 (Table 5, Figure 5). Trawl surveys conducted off California in 2004 and 2005 and the Pacific Northwest from 2003 to 2005 provide fishery-independent evidence for a strong 2003 year class. Length composition data from these surveys are displayed in Figure 21. Off the Pacific Northwest the 2003 year class first appeared in March 2004 as the length mode ranging 100-130 mm SL. This mode progressively appeared in subsequent surveys in July 2004 and March 2005 (Figure 21, top panel). Off California, the presumed 2003 year class appeared as the 140-180 mm SL mode in April 2005. Age determinations for the survey samples are pending.

Biomass of Stock for PFMC Management (Ages 1+)

Stock biomass (age 1+) estimates are presented in Table 13 and displayed in Figure 22. Stock biomass increased from low levels in the early 1980s to a peak of 1.49 million mt in 1996-97. The stock has subsequently declined to lower levels and was estimated to be approximately 1.06 million mt as of July 1, 2005. The biomass trend from the current assessment peaks several years earlier, and at a slightly higher level than presented in Conser et al. (2004) (Figure 22). This difference is attributed to the change in estimated recruitments (Figure 18), driven in part by the new Aerial Survey GLM time series.

Model Diagnostic Examinations

For the most part, diagnostics were reasonable. In particular, the results were not characterized by the lack of fit in the some abundance indices that appeared in previous assessments.

Areas of Uncertainty

The principal areas of uncertainty are:

1. A coast-wide population survey has not been conducted since 1994. A synoptic survey is being planned for April 2006, hopefully including participation by Mexico and Canada;
2. Evidence exists for a shift in maturity schedule, but recent survey samples indicate high year to year variability. Weights-at-age in the California and Ensenada fishery data display high inter-annual variability, and there is a need to improve the weight-at-age vector applied to population numbers for modeling and management purposes. Adult samples collected during the April 2006 synoptic survey should address both areas of uncertainty;
3. Stock structure and migration rates are not well understood and require further research efforts.

HARVEST GUIDELINE FOR 2006

The harvest guideline recommended for the USA (California, Oregon, and Washington) Pacific sardine fishery for calendar year 2006 is 118,937 mt. Statistics used to determine this harvest guideline are discussed below and presented in Table 14. To calculate the proposed harvest guideline for 2006, we used the maximum sustainable yield (MSY) control rule defined in Amendment 8 of the Coastal Pelagic Species-Fishery Management Plan, Option J, Table 4.2.5-1, PFMC (1998). This formula is intended to prevent Pacific sardine from being overfished and maintain relatively high and consistent catch levels over a long-term horizon. The Amendment 8 harvest formula for sardine is:

$$HG_{2006} = (\text{BIOMASS}_{2005} - \text{CUTOFF}) \cdot \text{FRACTION} \cdot \text{DISTRIBUTION}$$

where HG_{2006} is the total USA (California, Oregon, and Washington) harvest guideline recommended for 2006, BIOMASS_{2005} is the estimated July 1, 2005 stock biomass (ages 1+) from the current assessment (1,061,391 mt; see above), CUTOFF is the lowest level of estimated biomass at which harvest is allowed (150,000 mt), FRACTION is an environment-based percentage of biomass above the CUTOFF that can be harvested by the fisheries (see below), and DISTRIBUTION (87%) is the percentage of BIOMASS_{2005} assumed in U.S. waters. The value for FRACTION in the MSY control rule for Pacific sardine is a proxy for F_{msy} (i.e., the fishing mortality rate that achieves equilibrium MSY). Given F_{msy} and the productivity of the sardine stock have been shown to increase when relatively warm-ocean conditions persist, the following formula has been used to determine an appropriate (sustainable) FRACTION value:

$$\text{FRACTION or } F_{\text{msy}} = 0.248649805(T^2) - 8.190043975(T) + 67.4558326,$$

where T is the running average sea-surface temperature at Scripps Pier, La Jolla, California during the three preceding seasons (July-June). Ultimately, under Option J (PFMC 1998), F_{msy} is constrained and ranges between 5% and 15%. Based on the T values observed throughout the period covered by this stock assessment (1982-2005; Table 8, Figure 23), the appropriate F_{msy} exploitation fraction has consistently been 15%; and this remains the case under current oceanic conditions ($T_{2005} = 18.03$ °C). The 2006 USA harvest guideline (118,937 mt) is 13% lower than the 2005 harvest guideline (136,179 mt), but 22,049 mt higher than the highest recent harvest by the U.S. fisheries (96,896 mt in 2002; Table 15). Recent fishery practices and market conditions indicate the lower HG may not be constraining with regard to USA fishery landings in 2006 (PFMC 2005).

However, recent recruitment levels are not well-estimated, resulting in a high degree of uncertainty with respect to recent recruitment. If the actual recruitment in recent years is less than that estimated in the model and/or should the general sea-surface temperature decline continue, it is likely that harvest guidelines in the out years will constrain USA fishery practices and removals. Further when viewed on a stock-wide basis and considering the landings of Mexico and Canada as well as the USA (Table 15; Figure 24), adherence to an implied 'stock-wide harvest guideline' may constrain fisheries even without recruitment and sea-surface temperature declines.

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Table 1. Maturity schedule applied in the baseline model to calculate spawning stock biomass.

Coded Age (ASAP)	True Age	% Mature
1	0	30
2	1	53
3	2	91
4	3	97
5	4	99
6	5+	100

Table 2. Pacific sardine landings (mt) and sample sizes (number of fish) for production of fishery catches-at-age (see Tables 3-5).

Biological Year	----- CALIFORNIA -----			----- ENSENADA -----			-- PACIFIC NORTHWEST --		
	Landings (mt)	# Fish Sampled	Fish per 1,000 mt	Landings (mt)	# Fish Sampled	Fish per 1,000 mt	Landings (mt)	# Fish Sampled	Fish per 1,000 mt
1982-83	337	941	2,791	150	0	0	0	---	---
1983-84	248	599	2,413	124	0	0	0	---	---
1984-85	397	214	539	3,174	0	0	0	---	---
1985-86	1,191	1,150	965	647	0	0	0	---	---
1986-87	1,548	1,517	980	1,118	0	0	0	---	---
1987-88	3,810	2,855	749	2,077	0	0	0	---	---
1988-89	2,919	1,634	560	1,876	34	18	0	---	---
1989-90	3,659	1,486	406	11,663	170	15	0	---	---
1990-91	5,856	2,344	400	14,746	901	61	0	---	---
1991-92	9,574	2,040	213	25,447	2,179	86	0	---	---
1992-93	24,320	3,683	151	49,890	719	14	4	0	0
1993-94	12,431	1,148	92	19,108	346	18	0	---	---
1994-95	32,902	3,668	111	33,393	494	15	0	---	---
1995-96	29,820	2,626	88	32,835	500	15	23	0	0
1996-97	29,027	4,509	155	36,897	478	13	44	0	0
1997-98	56,172	4,305	77	75,179	485	6	28	0	0
1998-99	51,005	4,463	88	62,333	537	9	563	31	55
1999-00	60,360	2,672	44	57,743	553	10	1,155	178	154
2000-01	52,916	3,196	60	50,457	512	10	17,923	2,006	112
2001-02	52,981	4,283	81	46,948	362	8	25,683	2,581	100
2002-03	60,714	3,216	53	44,938	55	1	36,123	2,834	78
2003-04	29,650	3,572	120	37,040	0	0	39,860	2,488	62
2004-05	45,851	4,034	88	47,379	0	0	47,746	1,738	36

Table 3. Pacific sardine catch-at-age (thousands of fish) and landings (metric tons), 1982-2005 seasons (July-June), for the California fishery (Fishery 1). Landings for 2005 (i.e. 2005-06) were projected.

Biological Year	Catch-at-age (thousands)						Landings (mt)
	0	1	2	3	4	5+	
1982-83	0	880	1,261	261	56	8	337.2
1983-84	398	740	1,135	78	3	0	248.2
1984-85	17	804	1,611	282	0	0	397.0
1985-86	19	2,273	4,907	715	40	0	1,191.1
1986-87	185	1,167	5,924	2,305	175	26	1,548.2
1987-88	38	14,431	9,912	3,757	676	58	3,810.3
1988-89	356	4,999	11,193	2,602	786	109	2,919.0
1989-90	188	15,741	9,135	1,533	91	0	3,658.8
1990-91	1,350	9,506	14,557	10,456	5,050	2,919	5,855.6
1991-92	7,452	21,252	28,460	12,301	5,303	5,714	9,574.2
1992-93	33,463	147,999	98,106	22,749	5,997	3,354	24,319.9
1993-94	26,760	41,603	50,290	30,094	5,058	2,043	12,431.2
1994-95	206,712	236,588	64,598	29,723	4,091	868	32,902.4
1995-96	84,888	240,038	132,467	12,176	1,793	122	29,819.7
1996-97	89,636	96,347	136,744	57,311	7,157	2,119	29,026.8
1997-98	49,163	325,948	218,952	97,980	31,395	5,755	56,172.3
1998-99	219,059	601,996	183,576	25,483	14,214	1,990	51,005.2
1999-00	209,576	729,802	252,953	13,953	5,931	1,325	60,360.5
2000-01	173,501	260,540	283,685	157,218	12,562	1,851	52,915.6
2001-02	525,651	184,094	148,101	105,555	20,576	6,988	52,980.7
2002-03	126,574	568,045	156,788	31,379	10,102	2,505	60,713.6
2003-04	403,850	79,132	93,183	20,685	8,140	4,558	29,649.7
2004-05	27,554	734,286	88,954	12,512	2,853	893	45,851.2
2005-06	---	---	---	---	---	---	39,998.7

Table 4. Pacific sardine catch-at-age (thousands of fish) and landings (metric tons), 1982-2005 seasons (July-June), for the segment of the Mexican fishery that lands its product in Ensenada, Baja California, Mexico (Fishery 2). Ensenada landings for 2005-06 were based on incomplete data and projected.

Biological Year	Catch-at-age (thousands)						Landings (mt)
	0	1	2	3	4	5+	
1982-83	---	---	---	---	---	---	149.5
1983-84	---	---	---	---	---	---	124.1
1984-85	---	---	---	---	---	---	3,174.2
1985-86	---	---	---	---	---	---	647.3
1986-87	---	---	---	---	---	---	1,118.4
1987-88	---	---	---	---	---	---	2,076.8
1988-89	---	---	---	---	---	---	1,875.7
1989-90	30,029	35,488	15,431	4,272	1,887	66	11,663.2
1990-91	26,364	41,035	34,641	8,016	1,643	1,440	14,746.3
1991-92	20,559	68,135	50,263	41,932	18,599	8,898	25,447.3
1992-93	236,304	512,739	53,762	395	263	0	49,889.8
1993-94	103,939	69,104	120,215	8,697	0	0	19,108.4
1994-95	262,031	174,392	55,347	42,693	5,253	0	33,392.7
1995-96	191,289	144,459	85,039	17,658	5,799	0	32,834.8
1996-97	39,883	112,217	132,568	46,846	23,194	2,034	36,897.2
1997-98	44,799	157,950	266,468	184,200	79,962	23,397	75,179.4
1998-99	267,923	285,025	154,083	102,702	64,506	13,703	62,333.2
1999-00	393,256	288,886	164,243	81,932	31,978	13,576	57,743.0
2000-01	143,737	290,687	88,381	33,814	8,185	1,593	50,456.8
2001-02	221,428	236,772	145,254	14,659	1,715	0	46,948.1
2002-03	---	---	---	---	---	---	44,937.9
2003-04	---	---	---	---	---	---	37,040.3
2004-05	---	---	---	---	---	---	47,379.4
2005-06	---	---	---	---	---	---	47,379.4

Table 5. Pacific sardine catch-at-age (thousands of fish) and landings (metric tons), 1982-2005 seasons (July-June), for the fisheries off Oregon and Washington, USA and British Columbia, Canada (Fishery 3). Landings for 2005 (i.e. 2005-06) were projected.

Biological Year	Catch-at-age (thousands)						Landings (mt)
	0	1	2	3	4	5+	
1982-83	---	---	---	---	---	---	0.0
1983-84	---	---	---	---	---	---	0.0
1984-85	---	---	---	---	---	---	0.0
1985-86	---	---	---	---	---	---	0.0
1986-87	---	---	---	---	---	---	0.0
1987-88	---	---	---	---	---	---	0.0
1988-89	---	---	---	---	---	---	0.0
1989-90	---	---	---	---	---	---	0.0
1990-91	---	---	---	---	---	---	0.0
1991-92	---	---	---	---	---	---	0.0
1992-93	---	---	---	---	---	---	4.1
1993-94	---	---	---	---	---	---	0.0
1994-95	---	---	---	---	---	---	0.0
1995-96	---	---	---	---	---	---	22.7
1996-97	---	---	---	---	---	---	43.5
1997-98	---	---	---	---	---	---	28.0
1998-99	---	---	---	---	---	---	562.8
1999-00	0	0	3,791	1,937	1,040	2,262	1,154.6
2000-01	0	1,814	45,205	48,656	19,198	13,823	17,923.0
2001-02	178	3,499	21,320	70,724	44,439	26,569	25,682.9
2002-03	0	1,726	6,647	28,202	73,487	87,564	36,123.0
2003-04	0	4,538	38,538	37,039	25,874	129,242	39,860.2
2004-05	0	141,867	47,637	46,185	27,292	96,306	47,746.3
2005-06	---	---	---	---	---	---	48,384.0

Table 6. Pacific sardine fishery weight-at-age (kg), 1982-2005 seasons (July-June). Values are weighted estimates based on landings of the three respective fisheries.

Biological Year	Fishery Weight-at-age (kg)					
	0	1	2	3	4	5+
1982-83	0.069	0.118	0.128	0.155	0.184	0.187
1983-84	0.069	0.087	0.138	0.154	0.167	0.187
1984-85	0.083	0.108	0.135	0.148	0.164	0.160
1985-86	0.074	0.117	0.148	0.170	0.185	0.186
1986-87	0.054	0.111	0.150	0.164	0.184	0.172
1987-88	0.087	0.107	0.142	0.169	0.183	0.187
1988-89	0.069	0.101	0.148	0.169	0.185	0.195
1989-90	0.109	0.130	0.153	0.161	0.170	0.165
1990-91	0.082	0.122	0.143	0.152	0.155	0.159
1991-92	0.059	0.097	0.132	0.146	0.157	0.169
1992-93	0.054	0.062	0.095	0.123	0.161	0.146
1993-94	0.047	0.070	0.079	0.082	0.131	0.146
1994-95	0.050	0.062	0.087	0.095	0.102	0.115
1995-96	0.057	0.069	0.079	0.096	0.111	0.116
1996-97	0.063	0.077	0.107	0.114	0.121	0.122
1997-98	0.049	0.073	0.094	0.114	0.118	0.118
1998-99	0.042	0.056	0.078	0.103	0.104	0.115
1999-00	0.051	0.056	0.063	0.065	0.071	0.093
2000-01	0.057	0.078	0.089	0.096	0.106	0.126
2001-02	0.042	0.070	0.101	0.114	0.132	0.145
2002-03	0.054	0.084	0.100	0.113	0.128	0.145
2003-04	0.046	0.088	0.101	0.113	0.136	0.150
2004-05	0.048	0.066	0.097	0.116	0.130	0.156
2005-06	0.048	0.066	0.097	0.116	0.130	0.156

Table 7. Pacific sardine population weight-at-age (kg) used to calculate the total stock biomass (Ages 1+) for management, and population SSB as presented in Table 13.

Biological Year	----- Population Weight-at-age (kg) -----					
	0	1	2	3	4	5+
1982-83	0.033	0.103	0.147	0.168	0.172	0.179
1983-84	0.033	0.103	0.147	0.168	0.172	0.179
1984-85	0.033	0.103	0.147	0.168	0.172	0.179
1985-86	0.033	0.103	0.147	0.168	0.172	0.179
1986-87	0.033	0.103	0.147	0.168	0.172	0.179
1987-88	0.033	0.103	0.147	0.168	0.172	0.179
1988-89	0.033	0.103	0.147	0.168	0.172	0.179
1989-90	0.033	0.103	0.147	0.168	0.172	0.179
1990-91	0.033	0.103	0.147	0.168	0.172	0.179
1991-92	0.033	0.103	0.147	0.168	0.172	0.179
1992-93	0.033	0.103	0.147	0.168	0.172	0.179
1993-94	0.033	0.103	0.147	0.168	0.172	0.179
1994-95	0.033	0.103	0.147	0.168	0.172	0.179
1995-96	0.033	0.103	0.147	0.168	0.172	0.179
1996-97	0.033	0.103	0.147	0.168	0.172	0.179
1997-98	0.033	0.103	0.147	0.168	0.172	0.179
1998-99	0.033	0.103	0.147	0.168	0.172	0.179
1999-00	0.033	0.103	0.147	0.168	0.172	0.179
2000-01	0.033	0.103	0.147	0.168	0.172	0.179
2001-02	0.033	0.103	0.147	0.168	0.172	0.179
2002-03	0.033	0.103	0.147	0.168	0.172	0.179
2003-04	0.033	0.103	0.147	0.168	0.172	0.179
2004-05	0.033	0.103	0.147	0.168	0.172	0.179
2005-06	0.033	0.103	0.147	0.168	0.172	0.179

Table 8. Pacific sardine time series of survey indices of relative abundance and sea-surface temperature, 1982-2005. The SST is a moving average of monthly SST observations for the three-year period prior to July 1st of the given year.

Biological Year	DEPM (SSB)		Aerial Spotter (pre-adult)		SST at SIO Pier (°C)
	Estimate (mt)	CV	Estimate (mt)	CV	
1982-83	---	---	---	---	17.05
1983-84	---	---	---	---	17.25
1984-85	---	---	---	---	17.58
1985-86	7,659	---	19,301	0.34	17.80
1986-87	15,704	---	10,177	0.32	17.87
1987-88	13,526	---	16,807	0.22	17.71
1988-89	---	---	9,880	0.27	17.55
1989-90	---	---	3,999	0.23	17.24
1990-91	---	---	19,781	0.15	17.19
1991-92	---	---	20,384	0.14	17.35
1992-93	---	---	107,743	0.14	17.61
1993-94	127,102	0.32	150,630	0.10	17.84
1994-95	79,997	0.60	70,240	0.12	17.97
1995-96	83,176	0.48	23,079	0.12	18.04
1996-97	409,579	0.31	30,414	0.18	18.07
1997-98	313,986	0.41	59,407	0.15	18.08
1998-99	282,248	0.42	22,651	0.15	18.47
1999-00	1,063,837	0.67	7,454	0.17	18.08
2000-01	790,925	0.45	739	0.44	17.75
2001-02	206,333	0.35	43,543	0.38	17.24
2002-03	485,121	0.36	12,082	0.42	17.31
2003-04	281,639	0.30	17,959	0.75	17.46
2004-05	619,320	0.54	2,005	1.03	17.60
2005-06	---	---	---	---	18.03

Table 9. Selectivities applied to survey data in the ASAP model. See survey sections for details.

Survey	Age					
	0	1	2	3	4	5+
DEPM						
1982-2005	0.30	0.53	0.91	0.97	0.99	1.00
Aerial Spotter						
1982-2005	1.00	1.00	0.59	0.18	0.03	0.00

Table 10. Likelihood components for the baseline model in which 136 parameters were estimated. See text for definitions of fleet (fishery) numbers and index numbers.

Component	RSS	nobs	Lambda	Likelihood	% of Total
Catch_Fleet_1	0.0021	24	100	0.2086	
Catch_Fleet_2	0.0055	24	100	0.5504	
Catch_Fleet_3	0.1217	24	100	12.1723	
Catch_Fleet_Total	0.1293	72	100	12.9314	2%
Discard_Fleet_1	0.0000	24	0	0.0000	
Discard_Fleet_2	0.0000	24	0	0.0000	
Discard_Fleet_3	0.0000	24	0	0.0000	
Discard_Fleet_Total	0.0000	72	0	0.0000	
CAA_proportions	na	432	na	208.2440	39%
Discard_proportions	na	432	na	0.0000	
Index_Fit_1	12.3232	15	1	62.3062	
Index_Fit_2	35.2134	20	1	127.3310	
Index_Fit_Total	47.5366	35	2	189.6370	36%
Selectivity_devs_fleet_1	15.0597	1	0	0.0000	
Selectivity_devs_fleet_2	0.0000	1	0	0.0000	
Selectivity_devs_fleet_3	0.0000	1	0	0.0000	
Selectivity_devs_Total	15.0597	3	0	0.0000	0%
Catchability_devs_index_1	0.0000	15	10	0.0000	
Catchability_devs_index_2	0.0000	20	10	0.0000	
Catchability_devs_Total	0.0000	35	20	0.0000	0%
Fmult_fleet_1	6.5107	23	1	6.5107	
Fmult_fleet_2	15.2223	23	1	15.2223	
Fmult_fleet_3	53.8653	23	1	53.8653	
Fmult_fleet_Total	75.5983	69	3	75.5983	14%
N_year_1	0.0000	5	0	0.0000	
Stock-Recruit_Fit	14.5603	24	1	30.1618	6%
Recruit_devs	14.5603	24	1	14.5603	3%
SRR_steepness	0.0014	1	0	0.0000	
SRR_virgin_stock	0.0601	1	0	0.0000	
Curvature_over_age	20.6278	12	0	0.0000	
Curvature_over_time	30.1193	396	0	0.0000	
F_penalty	1.9479	144	0.001	0.0019	
Mean_Sel_year1_pen	0.0000	18	1000	0.0000	
Max_Sel_penalty	2.5512	1	100	0.0000	
Fmult Max_penalty	0.0000	?	100	0.0000	
TOTAL	222.7521	1776		531.1347	100%

Table 11. ASAP parameter estimates and standard deviations for the baseline model. The first 136 parameters are formal model parameters. The remaining are state variables derived from the formal model parameters. See text for definition of coded ages, fisheries, and indices.

Coded Age	Biol. Year	Fishery	Param #	Parameter	Estimate	Std. Dev.
1	1982	1	1	log_sel_year1	-5.29E+00	1.43E+02
2	1982	1	2	log_sel_year1	-1.78E+00	1.43E+02
3	1982	1	3	log_sel_year1	-3.75E-01	1.43E+02
4	1982	1	4	log_sel_year1	-7.96E-01	1.43E+02
5	1982	1	5	log_sel_year1	-1.57E+00	1.43E+02
6	1982	1	6	log_sel_year1	-2.17E+00	1.43E+02
1	1982	2	7	log_sel_year1	-2.64E+00	2.45E+02
2	1982	2	8	log_sel_year1	-1.84E+00	2.45E+02
3	1982	2	9	log_sel_year1	-1.70E+00	2.45E+02
4	1982	2	10	log_sel_year1	-2.07E+00	2.45E+02
5	1982	2	11	log_sel_year1	-2.43E+00	2.45E+02
6	1982	2	12	log_sel_year1	-4.05E+00	2.45E+02
1	1982	3	13	log_sel_year1	-6.00E+00	2.25E-02
2	1982	3	14	log_sel_year1	-1.95E+00	1.51E+00
3	1982	3	15	log_sel_year1	-1.70E-01	1.47E+00
4	1982	3	16	log_sel_year1	4.49E-01	1.47E+00
5	1982	3	17	log_sel_year1	9.37E-01	1.48E+00
6	1982	3	18	log_sel_year1	4.07E-01	1.48E+00
1	1982	1	19	log_sel_devs_vector	3.56E+00	7.83E-01
2	1982	1	20	log_sel_devs_vector	1.23E+00	7.28E-01
3	1982	1	21	log_sel_devs_vector	-8.86E-02	7.24E-01
4	1982	1	22	log_sel_devs_vector	-1.31E-01	7.39E-01
5	1982	1	23	log_sel_devs_vector	-2.78E-01	8.24E-01
6	1982	1	24	log_sel_devs_vector	-8.81E-01	9.70E-01
1	1982	2	25	log_sel_devs_vector	0.00E+00	5.81E+03
2	1982	2	26	log_sel_devs_vector	0.00E+00	5.81E+03
3	1982	2	27	log_sel_devs_vector	0.00E+00	5.81E+03
4	1982	2	28	log_sel_devs_vector	0.00E+00	5.81E+03
5	1982	2	29	log_sel_devs_vector	0.00E+00	5.81E+03
6	1982	2	30	log_sel_devs_vector	0.00E+00	5.81E+03
1	1982	3	31	log_sel_devs_vector	0.00E+00	5.81E+03
2	1982	3	32	log_sel_devs_vector	0.00E+00	5.81E+03
3	1982	3	33	log_sel_devs_vector	0.00E+00	5.81E+03
4	1982	3	34	log_sel_devs_vector	0.00E+00	5.81E+03
5	1982	3	35	log_sel_devs_vector	0.00E+00	5.81E+03
6	1982	3	36	log_sel_devs_vector	0.00E+00	5.81E+03
---	1982	1	37	log_Fmult_year1	-1.37E+00	1.43E+02
---	1982	2	38	log_Fmult_year1	-2.09E+00	2.45E+02
---	1982	3	39	log_Fmult_year1	-1.50E+01	1.09E-02
---	1983	1	40	log_Fmult_devs	-9.69E-01	1.42E-01
---	1984	1	41	log_Fmult_devs	-7.77E-01	1.31E-01
---	1985	1	42	log_Fmult_devs	3.57E-01	1.31E-01

Table 11 (cont'd). ASAP parameter estimates and standard deviations for the baseline model.

Coded Age	Biol. Year	Fishery	Param #	Parameter	Estimate	Std. Dev.
---	1986	1	43	log_Fmult_devs	-1.15E-01	1.31E-01
---	1987	1	44	log_Fmult_devs	5.31E-01	1.35E-01
---	1988	1	45	log_Fmult_devs	-8.06E-01	1.26E-01
---	1989	1	46	log_Fmult_devs	-1.83E-01	1.27E-01
---	1990	1	47	log_Fmult_devs	1.87E-01	1.18E-01
---	1991	1	48	log_Fmult_devs	5.29E-08	7.07E-01
---	1992	1	49	log_Fmult_devs	1.04E+00	1.09E-01
---	1993	1	50	log_Fmult_devs	-7.18E-01	1.10E-01
---	1994	1	51	log_Fmult_devs	6.33E-01	1.11E-01
---	1995	1	52	log_Fmult_devs	-3.68E-01	1.08E-01
---	1996	1	53	log_Fmult_devs	-2.09E-01	1.05E-01
---	1997	1	54	log_Fmult_devs	8.73E-01	1.08E-01
---	1998	1	55	log_Fmult_devs	2.18E-01	1.08E-01
---	1999	1	56	log_Fmult_devs	3.66E-01	1.11E-01
---	2000	1	57	log_Fmult_devs	-2.31E-01	1.06E-01
---	2001	1	58	log_Fmult_devs	1.22E-01	1.08E-01
---	2002	1	59	log_Fmult_devs	-1.24E-03	1.21E-01
---	2003	1	60	log_Fmult_devs	-7.51E-01	1.18E-01
---	2004	1	61	log_Fmult_devs	2.78E-01	1.22E-01
---	2005	1	62	log_Fmult_devs	-7.84E-02	1.11E-01
---	1983	2	63	log_Fmult_devs	-1.02E+00	1.30E-01
---	1984	2	64	log_Fmult_devs	2.33E+00	1.20E-01
---	1985	2	65	log_Fmult_devs	-1.97E+00	1.11E-01
---	1986	2	66	log_Fmult_devs	1.72E-01	1.16E-01
---	1987	2	67	log_Fmult_devs	7.21E-02	1.19E-01
---	1988	2	68	log_Fmult_devs	-4.38E-01	1.09E-01
---	1989	2	69	log_Fmult_devs	1.27E+00	1.12E-01
---	1990	2	70	log_Fmult_devs	1.54E-01	1.07E-01
---	1991	2	71	log_Fmult_devs	5.00E-01	1.08E-01
---	1992	2	72	log_Fmult_devs	7.82E-01	1.07E-01
---	1993	2	73	log_Fmult_devs	-1.02E+00	1.08E-01
---	1994	2	74	log_Fmult_devs	2.29E-01	1.09E-01
---	1995	2	75	log_Fmult_devs	-2.55E-01	1.05E-01
---	1996	2	76	log_Fmult_devs	-6.45E-02	1.04E-01
---	1997	2	77	log_Fmult_devs	8.88E-01	1.06E-01
---	1998	2	78	log_Fmult_devs	1.06E-01	1.05E-01
---	1999	2	79	log_Fmult_devs	1.59E-01	1.09E-01
---	2000	2	80	log_Fmult_devs	-2.27E-01	1.05E-01
---	2001	2	81	log_Fmult_devs	8.23E-03	1.07E-01
---	2002	2	82	log_Fmult_devs	-1.17E-01	1.16E-01
---	2003	2	83	log_Fmult_devs	-3.00E-01	1.18E-01
---	2004	2	84	log_Fmult_devs	1.77E-01	1.16E-01
---	2005	2	85	log_Fmult_devs	2.69E-02	1.10E-01
---	1983	3	86	log_Fmult_devs	-8.37E-02	6.87E-01

Table 11 (cont'd). ASAP parameter estimates and standard deviations for the baseline model.

Coded Age	Biol. Year	Fishery	Param #	Parameter	Estimate	Std. Dev.
---	1984	3	87	log_Fmult_devs	-8.35E-02	6.87E-01
---	1985	3	88	log_Fmult_devs	-8.25E-02	6.86E-01
---	1986	3	89	log_Fmult_devs	-7.77E-02	6.85E-01
---	1987	3	90	log_Fmult_devs	-6.38E-02	6.79E-01
---	1988	3	91	log_Fmult_devs	-3.48E-02	6.68E-01
---	1989	3	92	log_Fmult_devs	3.60E-02	6.43E-01
---	1990	3	93	log_Fmult_devs	2.02E-01	5.96E-01
---	1991	3	94	log_Fmult_devs	6.72E-01	5.01E-01
---	1992	3	95	log_Fmult_devs	3.02E+00	3.09E-01
---	1993	3	96	log_Fmult_devs	-2.89E+00	2.81E-01
---	1994	3	97	log_Fmult_devs	7.36E-02	3.37E-01
---	1995	3	98	log_Fmult_devs	4.22E+00	2.50E-01
---	1996	3	99	log_Fmult_devs	2.71E-01	1.21E-01
---	1997	3	100	log_Fmult_devs	-4.92E-01	1.18E-01
---	1998	3	101	log_Fmult_devs	3.10E+00	1.15E-01
---	1999	3	102	log_Fmult_devs	1.19E+00	1.21E-01
---	2000	3	103	log_Fmult_devs	2.49E+00	1.07E-01
---	2001	3	104	log_Fmult_devs	3.67E-01	1.06E-01
---	2002	3	105	log_Fmult_devs	5.06E-01	1.11E-01
---	2003	3	106	log_Fmult_devs	1.76E-01	1.20E-01
---	2004	3	107	log_Fmult_devs	2.26E-01	1.29E-01
---	2005	3	108	log_Fmult_devs	-1.47E-01	1.54E-01
1	1982	---	109	log_recruit_devs	-3.30E+00	1.75E-01
1	1983	---	110	log_recruit_devs	4.21E-01	2.16E-01
1	1984	---	111	log_recruit_devs	9.76E-02	2.05E-01
1	1985	---	112	log_recruit_devs	-5.51E-01	1.99E-01
1	1986	---	113	log_recruit_devs	-5.41E-02	1.72E-01
1	1987	---	114	log_recruit_devs	-2.65E-01	1.58E-01
1	1988	---	115	log_recruit_devs	4.99E-03	1.30E-01
1	1989	---	116	log_recruit_devs	-2.17E-01	1.22E-01
1	1990	---	117	log_recruit_devs	-2.15E-01	1.24E-01
1	1991	---	118	log_recruit_devs	2.55E-01	1.10E-01
1	1992	---	119	log_recruit_devs	-8.82E-03	1.29E-01
1	1993	---	120	log_recruit_devs	6.02E-01	1.11E-01
1	1994	---	121	log_recruit_devs	9.09E-01	1.05E-01
1	1995	---	122	log_recruit_devs	4.74E-01	1.17E-01
1	1996	---	123	log_recruit_devs	2.37E-01	1.27E-01
1	1997	---	124	log_recruit_devs	3.61E-01	1.25E-01
1	1998	---	125	log_recruit_devs	4.00E-01	1.20E-01
1	1999	---	126	log_recruit_devs	8.95E-02	1.23E-01
1	2000	---	127	log_recruit_devs	-1.67E-01	1.34E-01
1	2001	---	128	log_recruit_devs	4.43E-01	1.26E-01
1	2002	---	129	log_recruit_devs	-3.57E-01	1.68E-01
1	2003	---	130	log_recruit_devs	8.95E-01	1.36E-01

Table 11 (cont'd). ASAP parameter estimates and standard deviations for the baseline model.

Coded Age	Biol. Year	Fishery	Param #	Parameter	Estimate	Std. Dev.
1	2004	---	131	log_recruit_devs	-4.96E-02	9.61E-02
1	2005	---	132	log_recruit_devs	9.96E-04	5.03E-02
---	1982	---	133	log_q_year1 (DEPM)	-1.33E+01	2.04E-01
---	1982	---	134	log_q_year1 (Aerial)	-1.33E+01	1.69E-01
---	---	---	135	log_SRR_virgin	1.40E+01	1.40E-01
---	---	---	136	SRR_steepness	6.74E-01	4.24E-02
---	1982	---	137	SSB	7.25E+03	6.49E+02
---	1983	---	138	SSB	1.49E+04	2.03E+03
---	1984	---	139	SSB	3.47E+04	5.57E+03
---	1985	---	140	SSB	5.62E+04	9.95E+03
---	1986	---	141	SSB	8.55E+04	1.58E+04
---	1987	---	142	SSB	1.43E+05	2.77E+04
---	1988	---	143	SSB	2.14E+05	4.26E+04
---	1989	---	144	SSB	3.49E+05	6.90E+04
---	1990	---	145	SSB	4.09E+05	7.96E+04
---	1991	---	146	SSB	4.63E+05	8.72E+04
---	1992	---	147	SSB	4.42E+05	8.23E+04
---	1993	---	148	SSB	4.65E+05	8.94E+04
---	1994	---	149	SSB	5.98E+05	1.08E+05
---	1995	---	150	SSB	7.41E+05	1.33E+05
---	1996	---	151	SSB	9.75E+05	1.72E+05
---	1997	---	152	SSB	9.28E+05	1.57E+05
---	1998	---	153	SSB	7.57E+05	1.28E+05
---	1999	---	154	SSB	5.85E+05	9.52E+04
---	2000	---	155	SSB	6.86E+05	1.20E+05
---	2001	---	156	SSB	6.69E+05	1.25E+05
---	2002	---	157	SSB	6.31E+05	1.23E+05
---	2003	---	158	SSB	6.61E+05	1.36E+05
---	2004	---	159	SSB	6.48E+05	1.37E+05
---	2005	---	160	SSB	6.78E+05	1.54E+05
1	1982	---	161	Recruits	1.69E+05	3.13E+04
1	1983	---	162	Recruits	3.21E+05	6.36E+04
1	1984	---	163	Recruits	4.57E+05	9.96E+04
1	1985	---	164	Recruits	5.04E+05	1.18E+05
1	1986	---	165	Recruits	1.22E+06	2.74E+05
1	1987	---	166	Recruits	1.33E+06	3.03E+05
1	1988	---	167	Recruits	2.38E+06	5.17E+05
1	1989	---	168	Recruits	2.33E+06	4.87E+05
1	1990	---	169	Recruits	2.82E+06	5.51E+05
1	1991	---	170	Recruits	4.74E+06	8.45E+05
1	1992	---	171	Recruits	3.77E+06	7.17E+05
1	1993	---	172	Recruits	6.86E+06	1.23E+06
1	1994	---	173	Recruits	9.46E+06	1.61E+06
1	1995	---	174	Recruits	6.51E+06	1.09E+06

Table 11 (cont'd). ASAP parameter estimates and standard deviations for the baseline model.

Coded Age	Biol. Year	Fishery	Param #	Parameter	Estimate	Std. Dev.
1	1996	---	175	Recruits	5.37E+06	8.48E+05
1	1997	---	176	Recruits	6.37E+06	8.91E+05
1	1998	---	177	Recruits	6.57E+06	8.68E+05
1	1999	---	178	Recruits	4.65E+06	6.81E+05
1	2000	---	179	Recruits	3.41E+06	5.76E+05
1	2001	---	180	Recruits	6.50E+06	1.07E+06
1	2002	---	181	Recruits	2.91E+06	6.13E+05
1	2003	---	182	Recruits	1.00E+07	1.89E+06
1	2004	---	183	Recruits	3.94E+06	6.81E+05
1	2005	---	184	Recruits	4.13E+06	6.34E+05
6	1982	---	185	plus_group	1.94E+03	0.00E+00
6	1983	---	186	plus_group	3.30E+03	3.69E+01
6	1984	---	187	plus_group	4.26E+03	5.36E+01
6	1985	---	188	plus_group	4.84E+03	8.32E+01
6	1986	---	189	plus_group	5.61E+03	1.27E+02
6	1987	---	190	plus_group	2.24E+04	4.06E+03
6	1988	---	191	plus_group	5.03E+04	1.02E+04
6	1989	---	192	plus_group	8.55E+04	1.83E+04
6	1990	---	193	plus_group	1.15E+05	2.53E+04
6	1991	---	194	plus_group	2.19E+05	5.03E+04
6	1992	---	195	plus_group	2.98E+05	6.98E+04
6	1993	---	196	plus_group	4.44E+05	1.10E+05
6	1994	---	197	plus_group	5.22E+05	1.31E+05
6	1995	---	198	plus_group	5.95E+05	1.50E+05
6	1996	---	199	plus_group	8.07E+05	1.99E+05
6	1997	---	200	plus_group	8.82E+05	2.12E+05
6	1998	---	201	plus_group	1.21E+06	2.87E+05
6	1999	---	202	plus_group	1.61E+06	3.82E+05
6	2000	---	203	plus_group	1.52E+06	3.72E+05
6	2001	---	204	plus_group	1.27E+06	3.29E+05
6	2002	---	205	plus_group	1.09E+06	3.03E+05
6	2003	---	206	plus_group	9.20E+05	2.86E+05
6	2004	---	207	plus_group	7.27E+05	2.53E+05
6	2005	---	208	plus_group	5.45E+05	2.16E+05

Table 12. Pacific sardine instantaneous rates of fishing mortality at age (yr^{-1}) for biological years 1982-2005. The biological year begins on July 1st and extends through June 30th of the labeled year.

Biological Year	Instantaneous Fishing Mortality Rate at Age (yr^{-1})					
	0	1	2	3	4	5+
1982-83	0.010	0.063	0.198	0.131	0.064	0.031
1983-84	0.004	0.023	0.075	0.049	0.024	0.012
1984-85	0.033	0.080	0.114	0.078	0.050	0.013
1985-86	0.005	0.021	0.055	0.037	0.019	0.008
1986-87	0.006	0.022	0.053	0.035	0.019	0.008
1987-88	0.006	0.029	0.081	0.054	0.027	0.012
1988-89	0.004	0.016	0.039	0.026	0.014	0.006
1989-90	0.014	0.036	0.059	0.040	0.024	0.007
1990-91	0.016	0.042	0.070	0.047	0.028	0.009
1991-92	0.033	0.082	0.093	0.062	0.039	0.008
1992-93	0.078	0.196	0.220	0.147	0.089	0.019
1993-94	0.031	0.080	0.089	0.059	0.035	0.008
1994-95	0.045	0.122	0.136	0.089	0.049	0.011
1995-96	0.034	0.089	0.099	0.066	0.037	0.009
1996-97	0.030	0.078	0.087	0.058	0.033	0.008
1997-98	0.072	0.187	0.210	0.139	0.080	0.018
1998-99	0.083	0.220	0.246	0.164	0.094	0.022
1999-00	0.106	0.287	0.322	0.214	0.122	0.031
2000-01	0.085	0.232	0.279	0.213	0.167	0.066
2001-02	0.090	0.251	0.309	0.246	0.205	0.087
2002-03	0.085	0.243	0.319	0.280	0.270	0.127
2003-04	0.052	0.147	0.222	0.231	0.270	0.139
2004-05	0.064	0.185	0.278	0.290	0.338	0.174
2005-06	0.063	0.178	0.262	0.265	0.301	0.152

Table 13. Pacific sardine population numbers at age (millions), spawning stock biomass (SSB, mt), and age 1+ biomass (mt) at the beginning of each biological year, 1982-83 to 2005-06 (July-June). ‘Model SSB’ is based on maturity-at-age (Table 1) and fishery weights-at-age (Table 6) and is used in ASAP to estimate stock-recruitment. ‘Population SSB’ and ‘Age 1+ biomass’ were calculated using population weights-at-age in Table 7. Total landings by biological year are also provided. Recruitment is shown as population numbers at age-0. Age 1+ biomass as of July 2005 (bold) serves as the basis for setting a harvest guideline for the U.S. fishery in calendar year 2006 (see Table 14).

Biological Year	--- Population Numbers-at-age (millions) ---						Model SSB	Population SSB	Age 1+ Biomass	Total Landings
	0	1	2	3	4	5+				
1982-83	169	15	9	5	3	2	7,246	5,473	4,680	487
1983-84	321	112	9	5	3	3	14,871	12,496	14,904	372
1984-85	457	214	73	6	3	4	34,686	28,279	35,138	3,571
1985-86	504	296	133	44	4	5	56,213	47,517	58,868	1,838
1986-87	1,216	336	195	84	28	6	85,527	75,915	83,202	2,667
1987-88	1,329	810	220	124	54	22	143,450	120,318	150,063	5,887
1988-89	2,383	885	528	136	79	50	214,310	187,013	214,092	4,795
1989-90	2,329	1,591	584	340	89	86	349,300	273,909	337,541	15,322
1990-91	2,821	1,540	1,029	369	219	115	409,240	367,603	430,119	20,602
1991-92	4,741	1,861	990	644	236	219	463,370	465,191	525,168	35,022
1992-93	3,774	3,073	1,149	605	405	298	441,710	579,719	710,205	74,214
1993-94	6,857	2,340	1,694	618	350	444	464,730	661,919	733,519	31,540
1994-95	9,457	4,457	1,449	1,039	390	522	598,180	859,955	1,007,344	66,295
1995-96	6,512	6,058	2,646	848	637	595	741,050	1,102,002	1,371,383	62,677
1996-97	5,370	4,222	3,716	1,606	532	807	975,310	1,276,872	1,486,348	65,968
1997-98	6,372	3,494	2,618	2,283	1,016	882	928,060	1,306,901	1,460,963	131,380
1998-99	6,571	3,976	1,942	1,423	1,332	1,209	757,010	1,217,091	1,379,803	113,901
1999-00	4,654	4,053	2,139	1,018	810	1,606	584,550	1,144,594	1,329,681	119,258
2000-01	3,415	2,804	2,039	1,039	551	1,525	686,100	995,543	1,130,737	121,295
2001-02	6,500	2,103	1,490	1,034	563	1,269	668,820	870,016	933,416	125,612
2002-03	2,907	3,982	1,097	734	542	1,088	631,000	799,575	982,860	141,775
2003-04	10,042	1,790	2,093	535	372	920	661,010	791,832	810,115	106,550
2004-05	3,943	6,394	1,036	1,124	284	727	648,240	888,489	1,179,103	140,977
2005-06	4,131	2,479	3,563	526	564	545	677,500	931,483	1,061,391	135,762

Table 14. Proposed harvest guideline for Pacific sardine for the 2005 management year. See 'Harvest Guideline' section for methods used to derive harvest guideline.

Stock biomass (age 1+, mt)	Cutoff (mt)	Fraction	Distribution	Harvest guideline (mt)
1,061,391	150,000	15%	87%	118,937

Table 15. Coast-wide harvest (mt) of Pacific sardine for calendar years 1983 through 2004.

Calendar Year	Ensenada (mt)	U.S. (mt)	Canada (mt)	Total (mt)
1983	274	1	0	274
1984	0	1	0	1
1985	3,722	6	0	3,728
1986	243	388	0	631
1987	2,432	439	0	2,871
1988	2,035	1,188	0	3,223
1989	6,224	837	0	7,061
1990	11,375	1,664	0	13,040
1991	31,392	7,587	0	38,979
1992	34,568	17,950	0	52,518
1993	32,045	15,345	0	47,390
1994	20,877	11,644	0	32,520
1995	35,396	40,327	25	75,748
1996	39,065	32,553	88	71,706
1997	68,439	43,245	34	111,718
1998	47,812	42,956	745	91,514
1999	58,569	60,039	1,250	119,858
2000	67,845	67,985	1,718	137,549
2001	46,071	75,800	1,600	123,472
2002	46,845	96,896	1,044	144,785
2003	41,342	71,864	954	114,159
2004	41,897	89,338	4,259	135,494

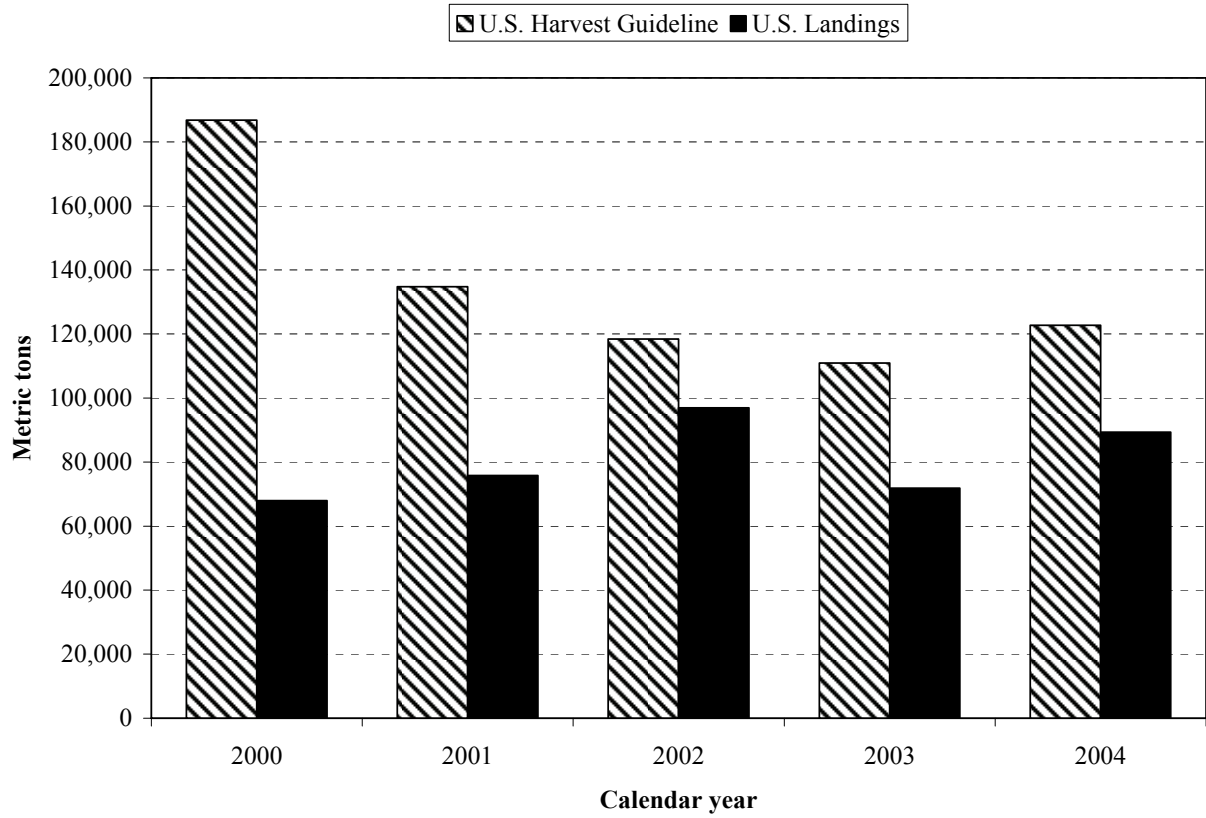


Figure 1. U.S. Pacific sardine harvest guidelines and resultant landings (mt) since the onset of PFMC management in calendar year 2000.

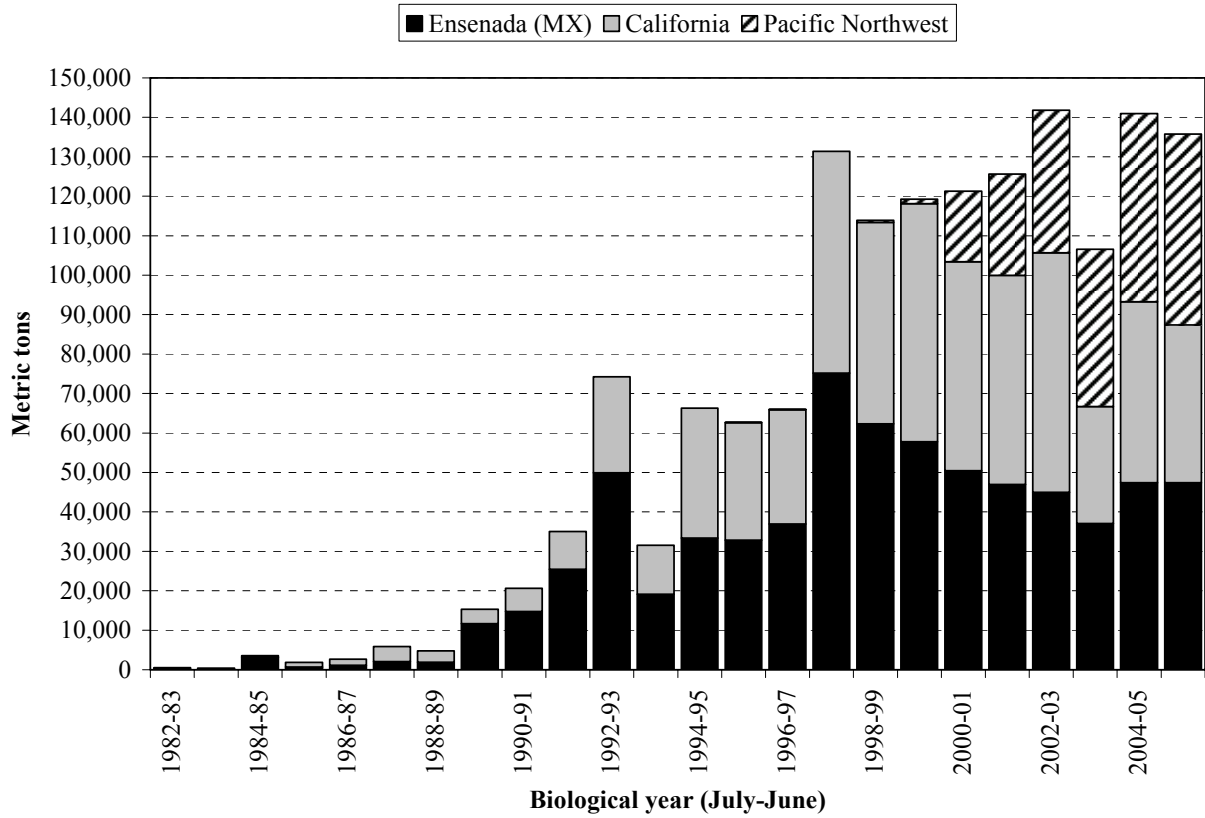


Figure 2. Pacific sardine landings (mt) by fishery for biological years 1982-2005 (July-June). Landings for 2005-06 were projected.

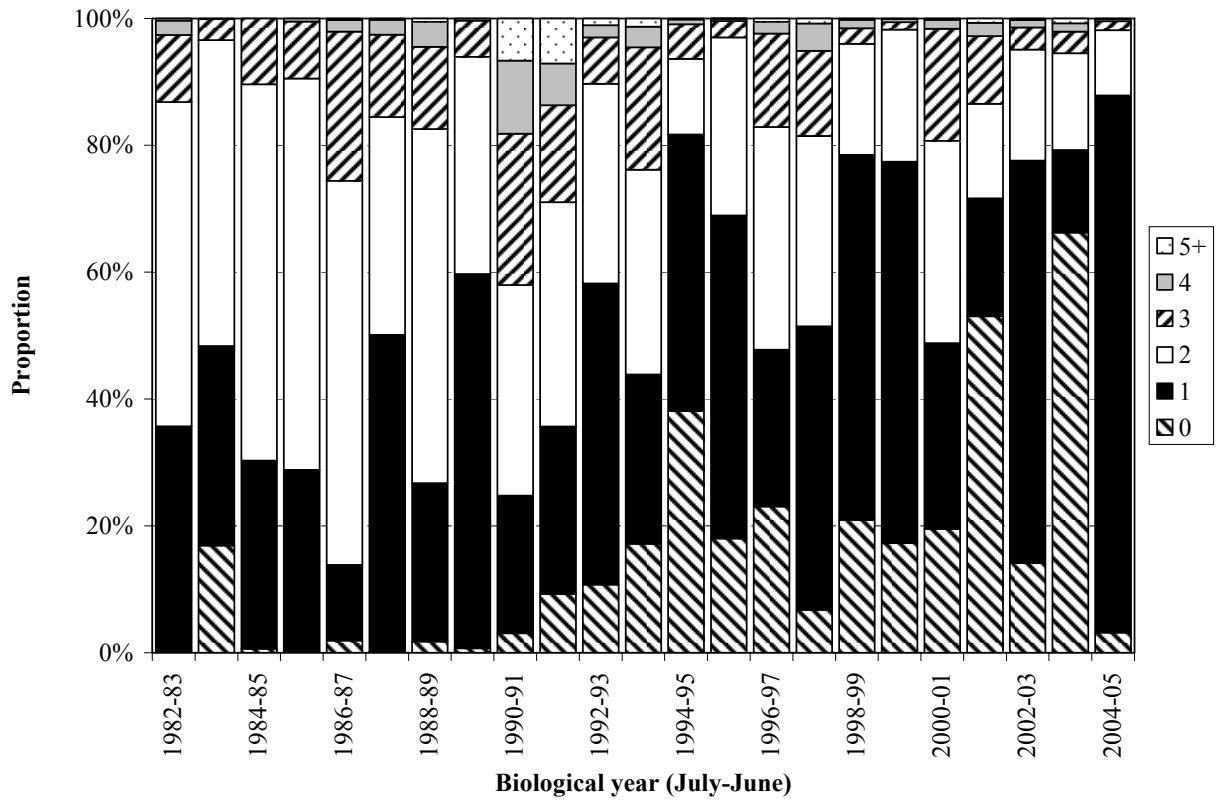


Figure 3. Catch-at-age proportions for the Pacific sardine fishery in California (San Pedro and Monterey) for the biological years 1982-2004 (July-June). See also Table 3.

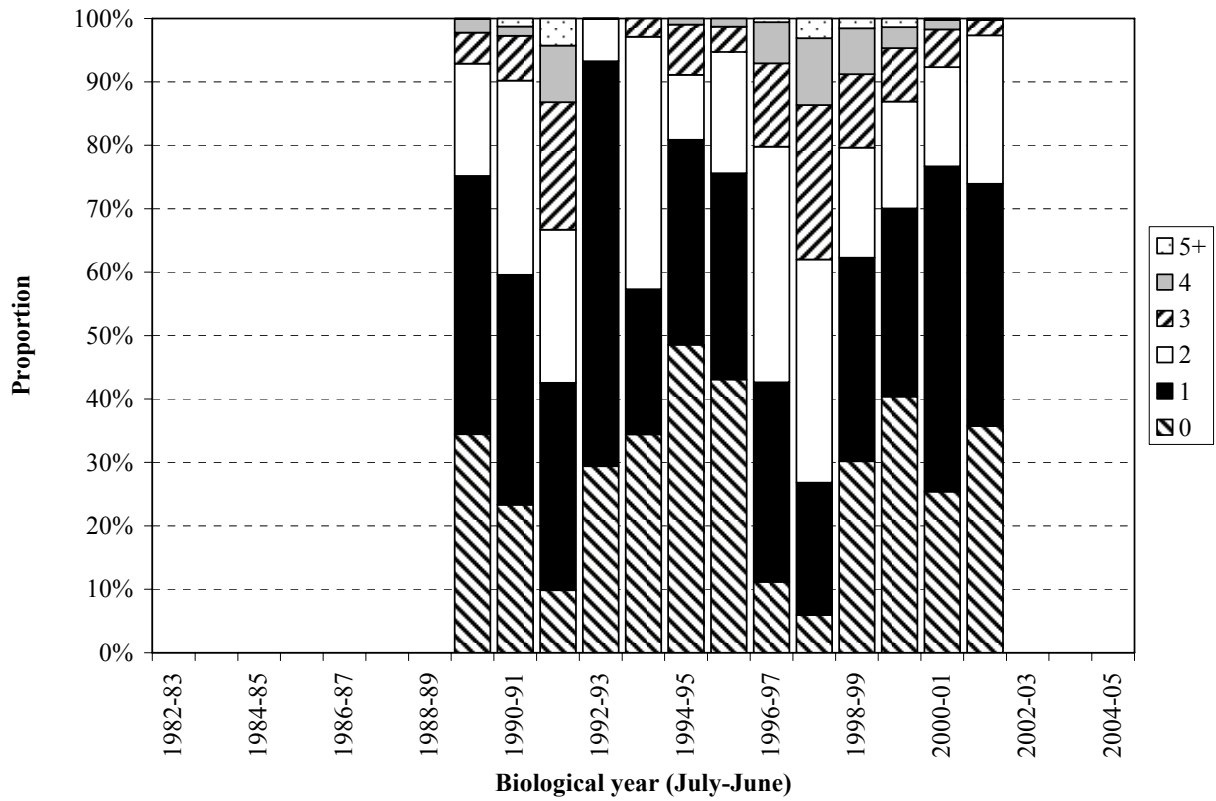


Figure 4. Catch-at-age proportions for the Pacific sardine fishery in Ensenada (Baja California, Mexico) for the biological years 1989-2001 (July-June). See also Table 4.

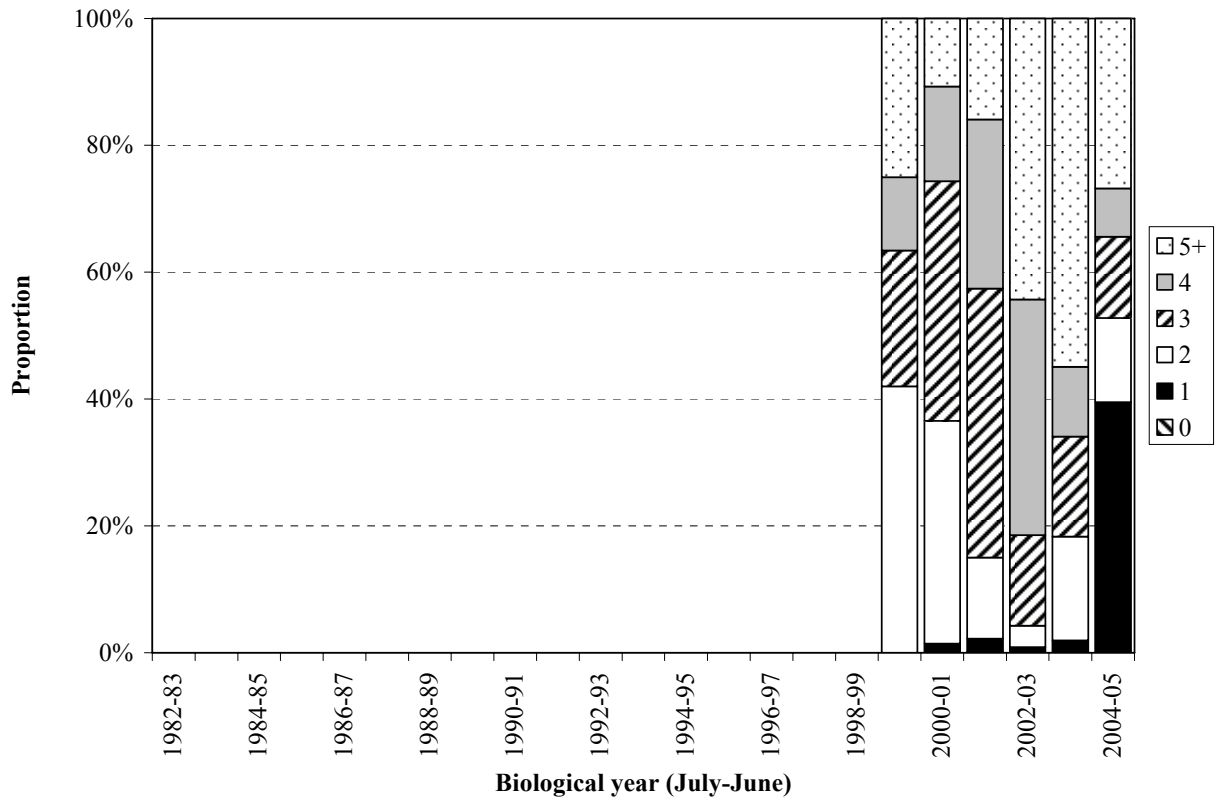


Figure 5. Catch-at-age proportions for the Pacific sardine fishery in the Pacific Northwest for biological years 1999-2004 (July-June). See also Table 5.

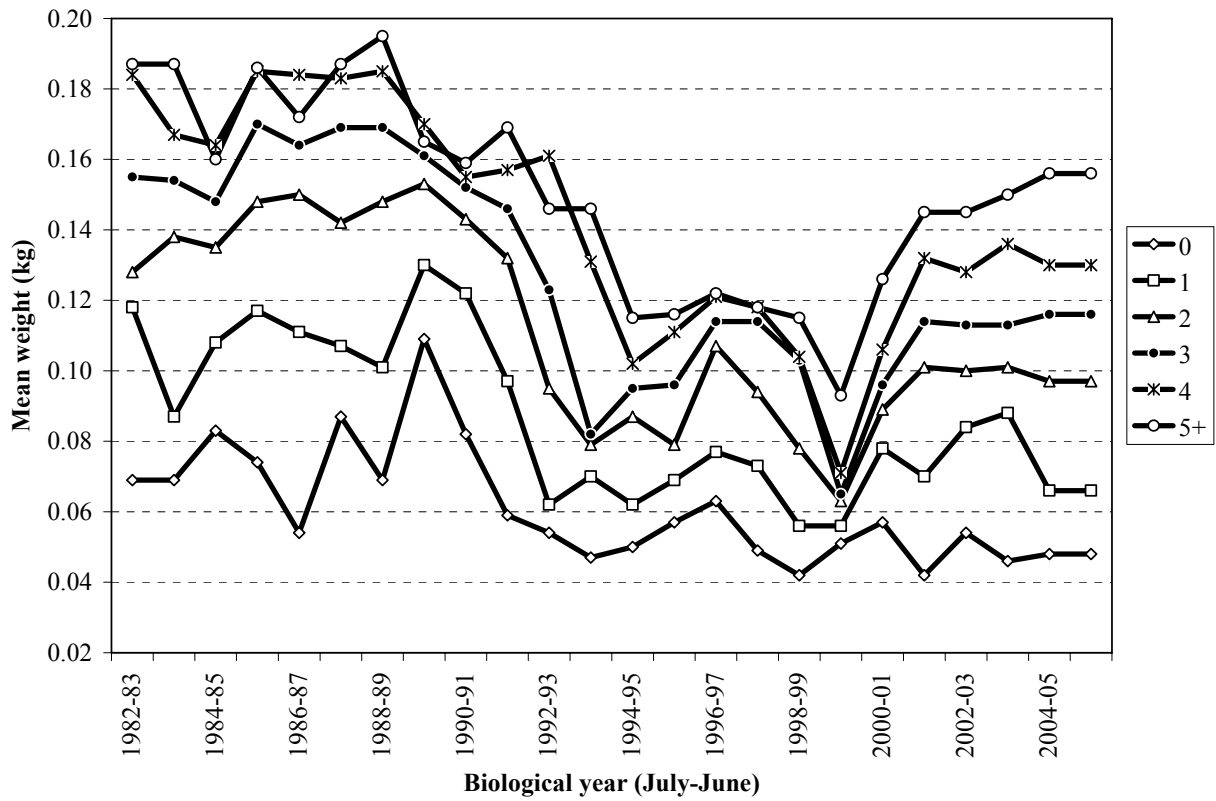


Figure 6. Pooled fishery weight-at-age (kg) for Pacific sardine as applied in the ASAP base model. Whole body weights were averaged across the three fisheries using respective landings to weight the data.

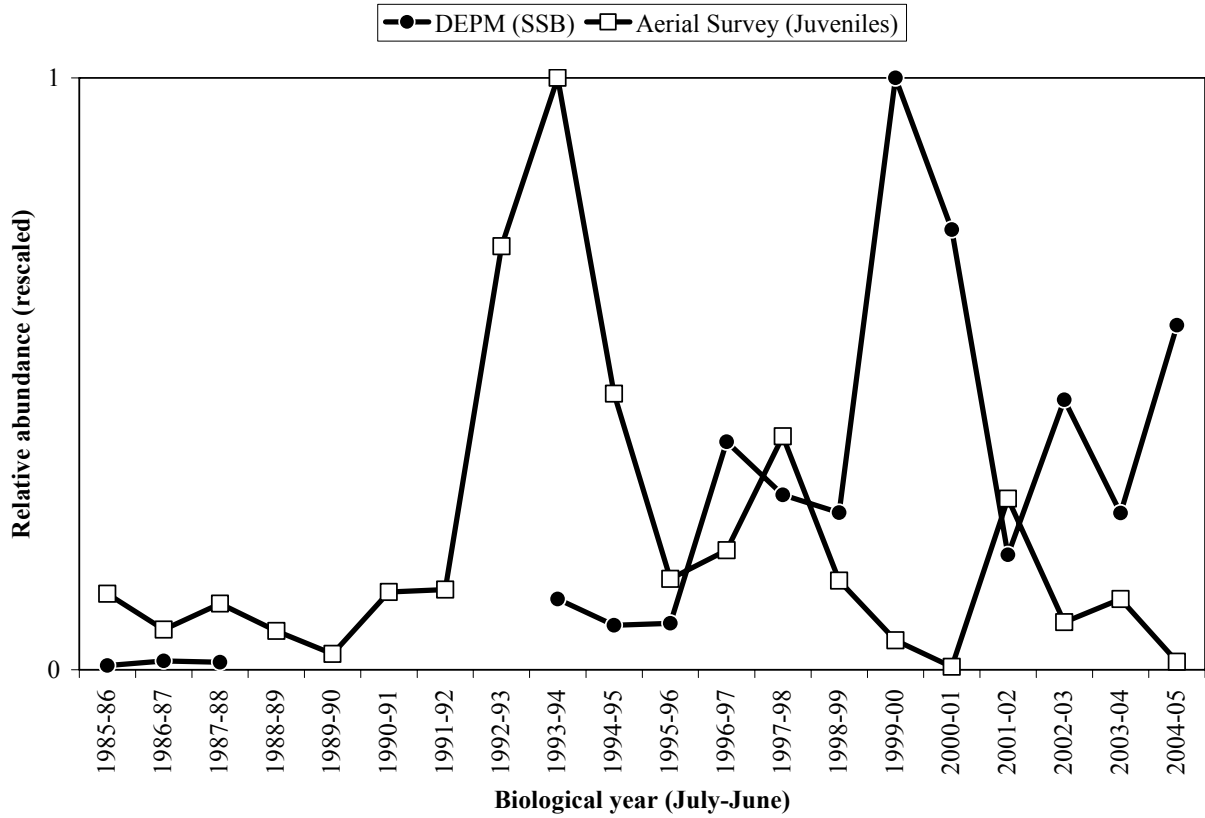


Figure 7. Indices of relative abundance for Pacific sardine applied in ASAP. Both indices are rescaled to a maximum value of 1 for comparison.

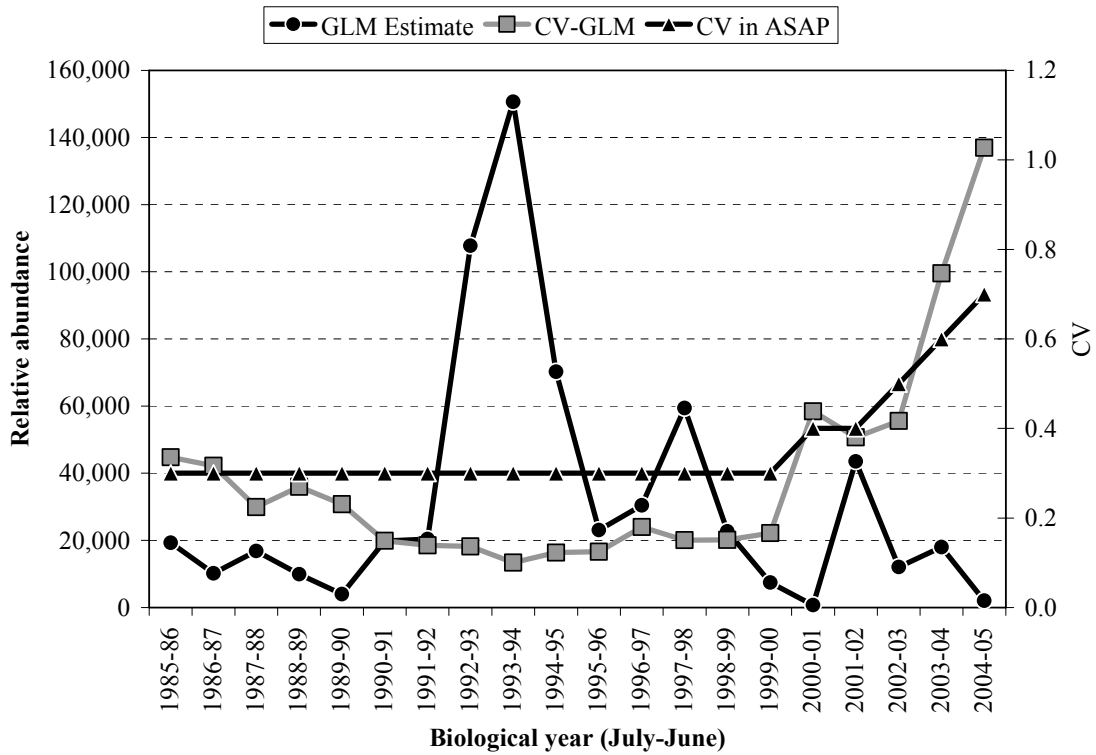


Figure 8. Aerial spotter survey index of relative abundance and coefficients of variation (CVs) from the GLM. CVs applied in the ASAP model are also displayed.

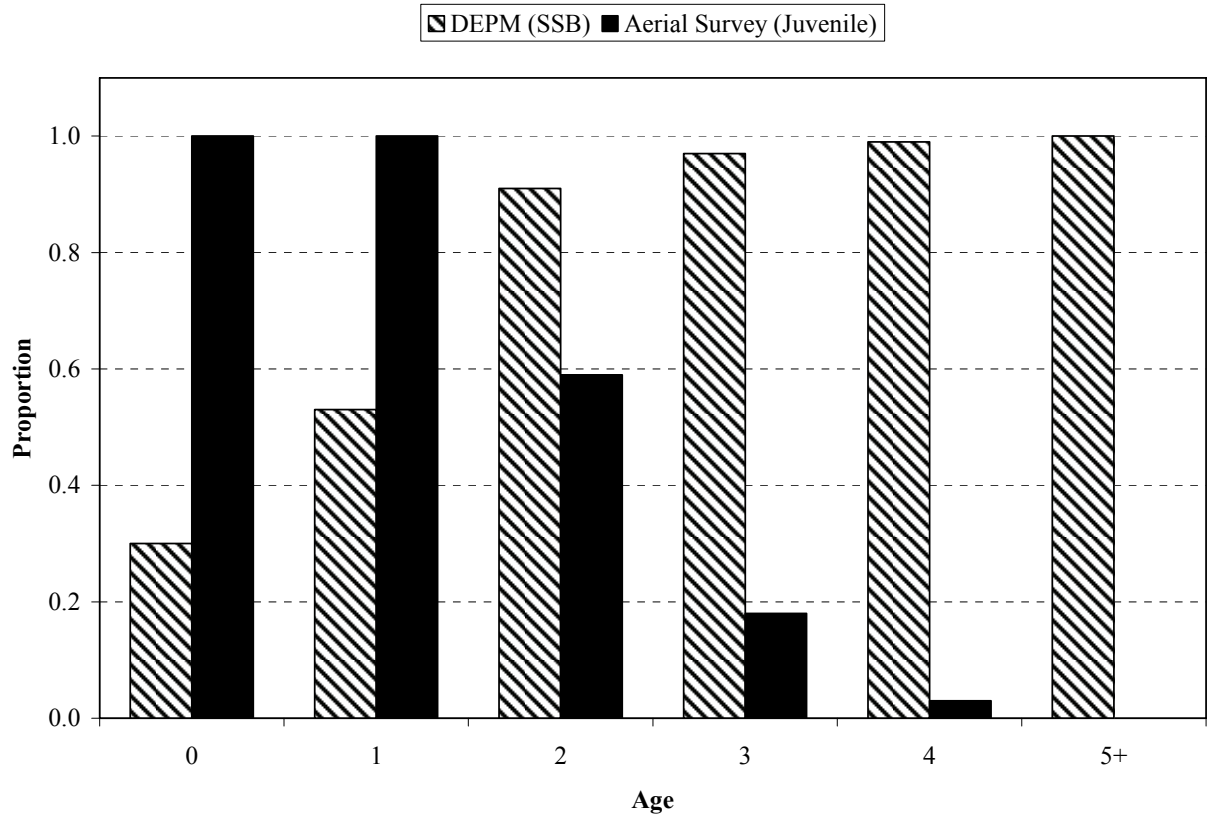


Figure 9. Selectivity ogives applied to Pacific sardine survey data in ASAP.

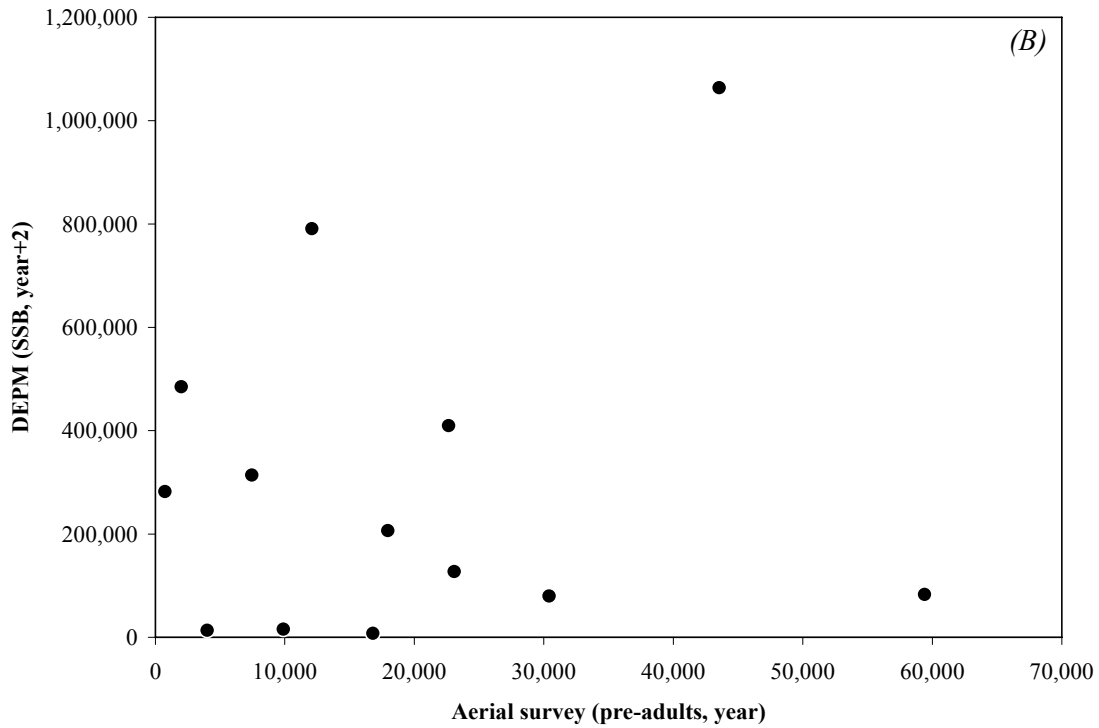
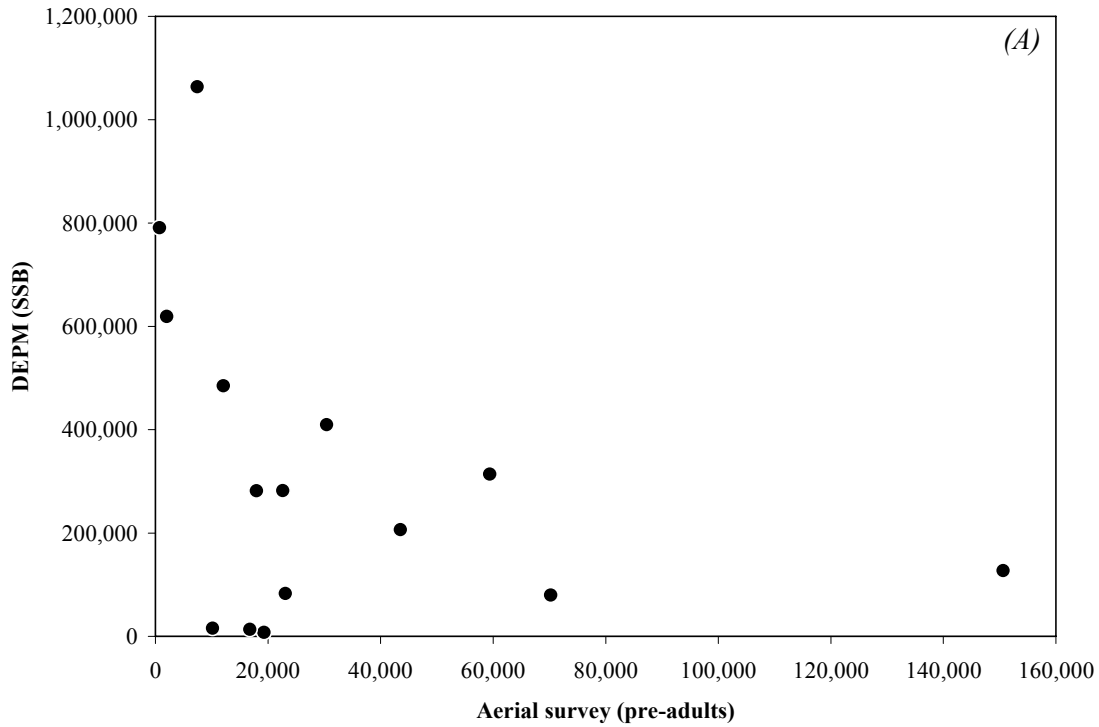


Figure 10. Comparisons of observed values for the DEPM survey (index of spawning stock biomass) and Aerial Spotter survey (index of young sardine): (A) year by year comparisons, and (B) surveys lagged two years, i.e. the aerial spotter index values were plotted against the DEPM index two years later.

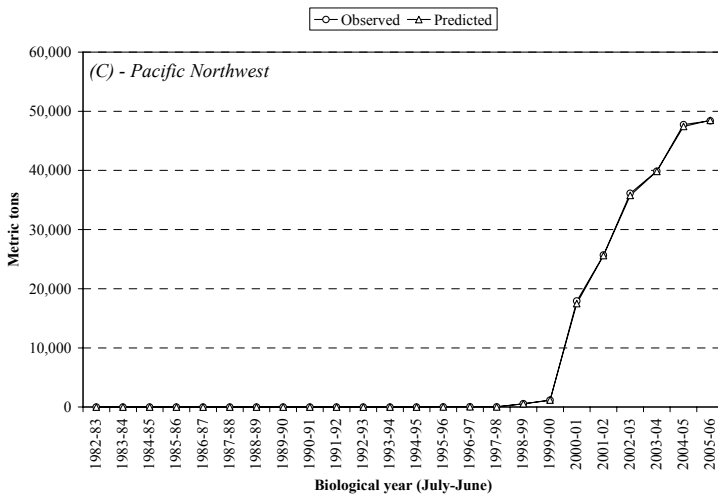
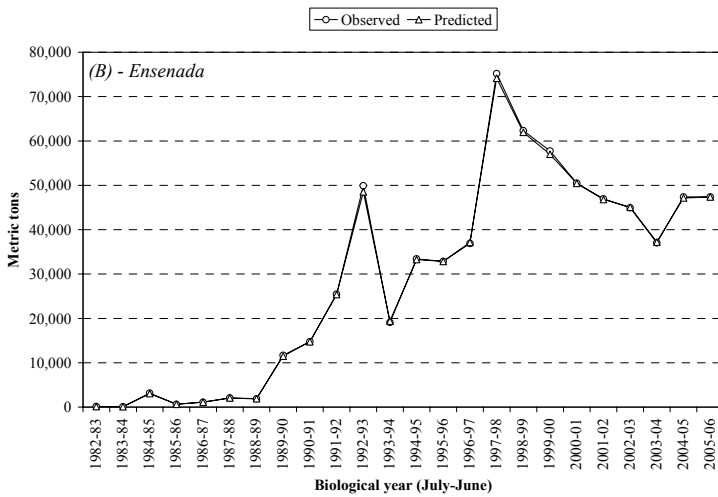
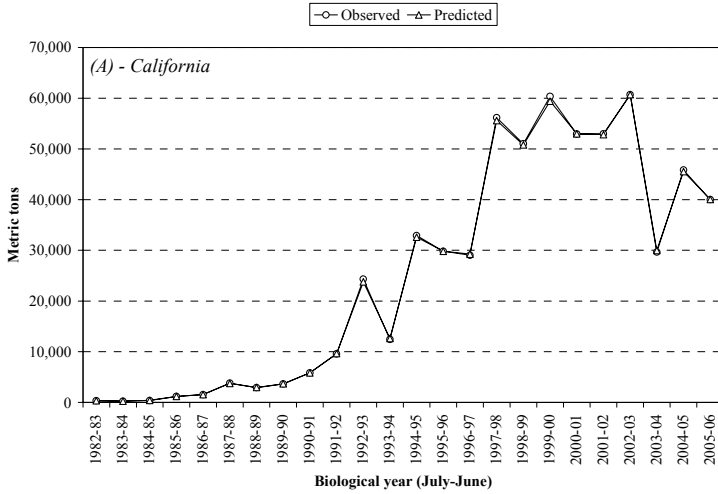


Figure 11. Observed and predicted estimates of total catch (mt) from the ASAP model (1982-2005): (A) California, (B) Ensenada, and (C) Pacific Northwest.

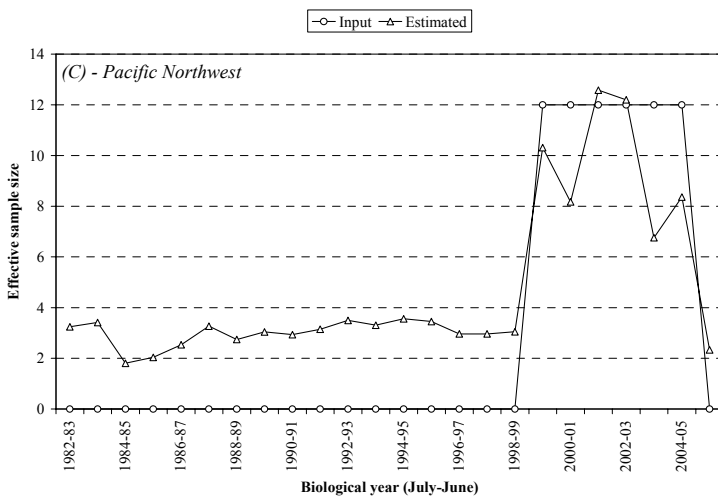
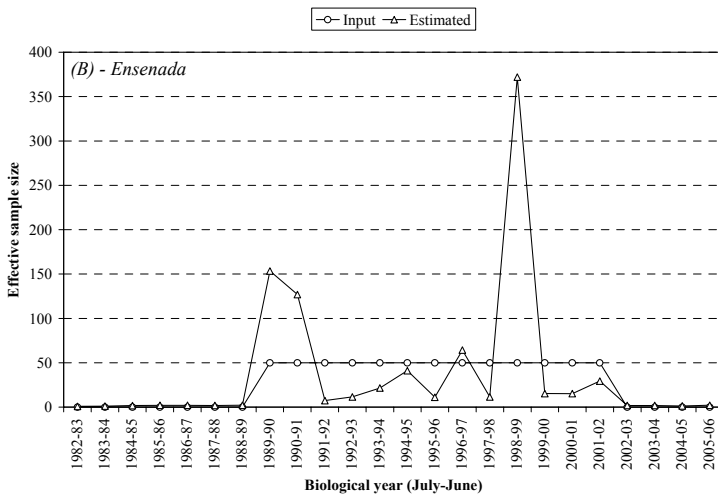
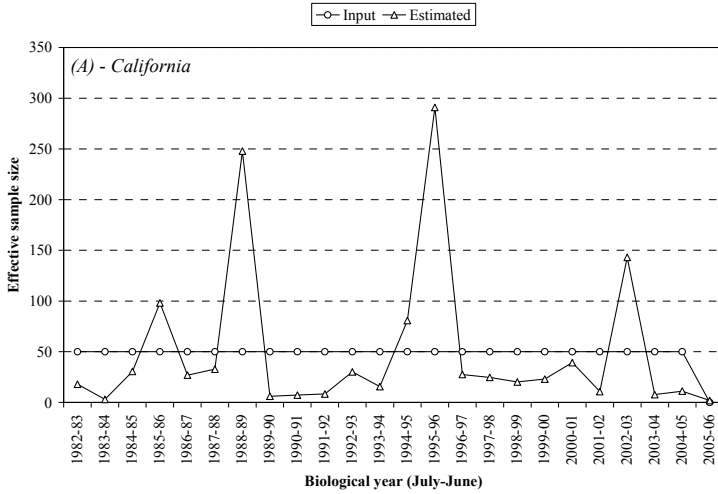


Figure 12. Effective sample sizes estimated for catch-at-age data from the (A) California, (B) Ensenada, and (C) Pacific northwest fisheries.

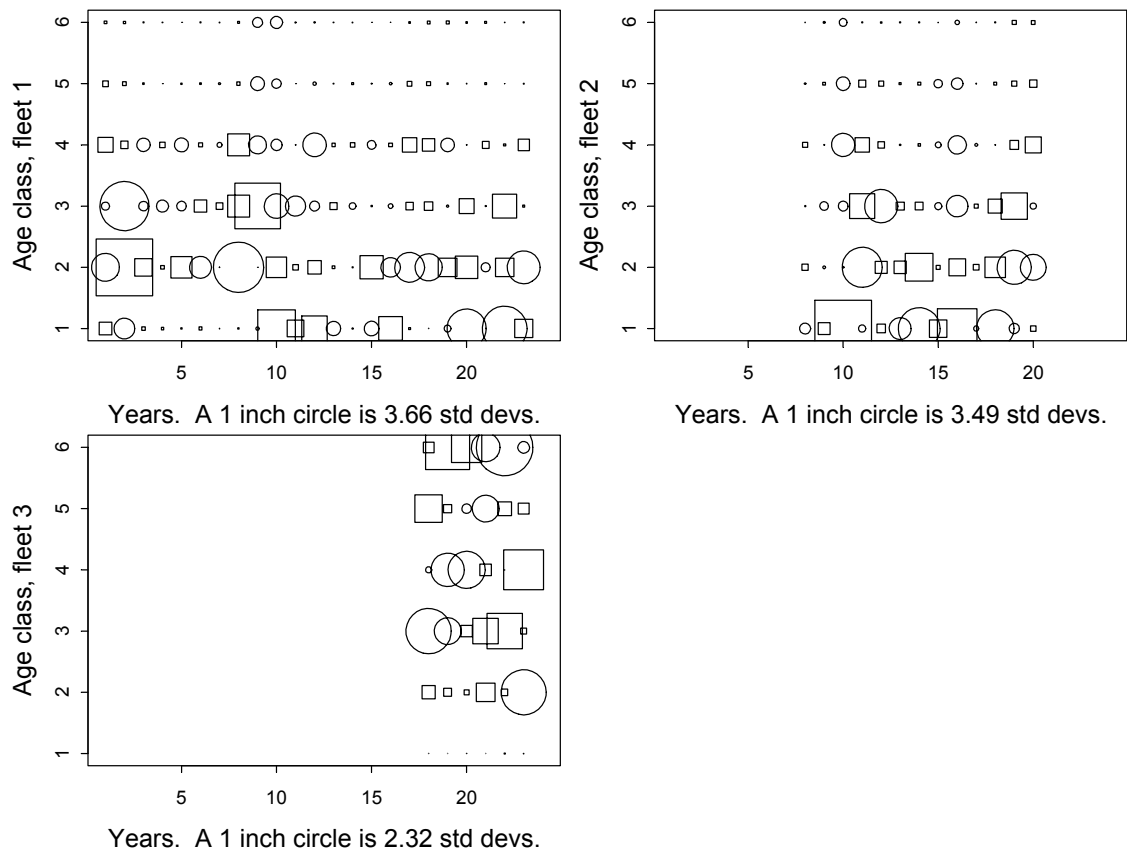


Figure 13. Standardized residuals from ASAP model fit to catch-at-age data for the three sardine fisheries (Fleet-1=CA; Fleet-2=MX; and Fleet-3=NW). Symbol size is proportional to the magnitude of the residual. Circles are positive and squares are negative residuals. Coded ages are shown on the ordinate of each plot (coded-age-1=true-age-0, coded-age-2=true-age-1,, coded-age-6=true-ages-5+). Biological years are shown on the abscissa of each plot (1=1982, 2=1983,, 23=2005).

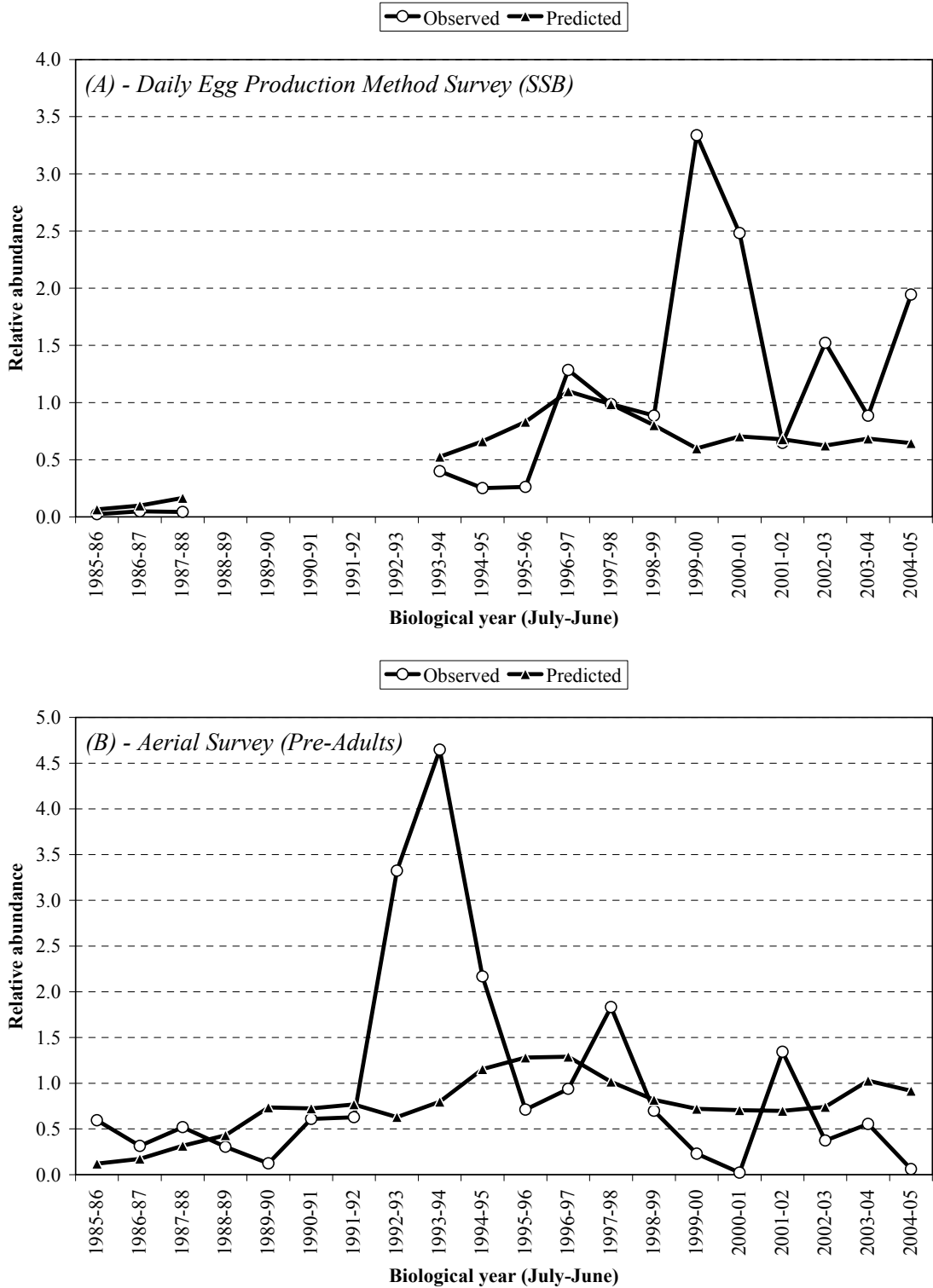


Figure 14. ASAP model fits to survey data: (A) Index of relative abundance of sardine spawning stock biomass (mt) based on daily egg production method (DEPM) estimates from ichthyoplankton survey data, 1985-85 to 2004-05; (B) Index of relative abundance of sardine pre-adult biomass (primarily age 0-2 fish) based on aerial spotter plane survey.

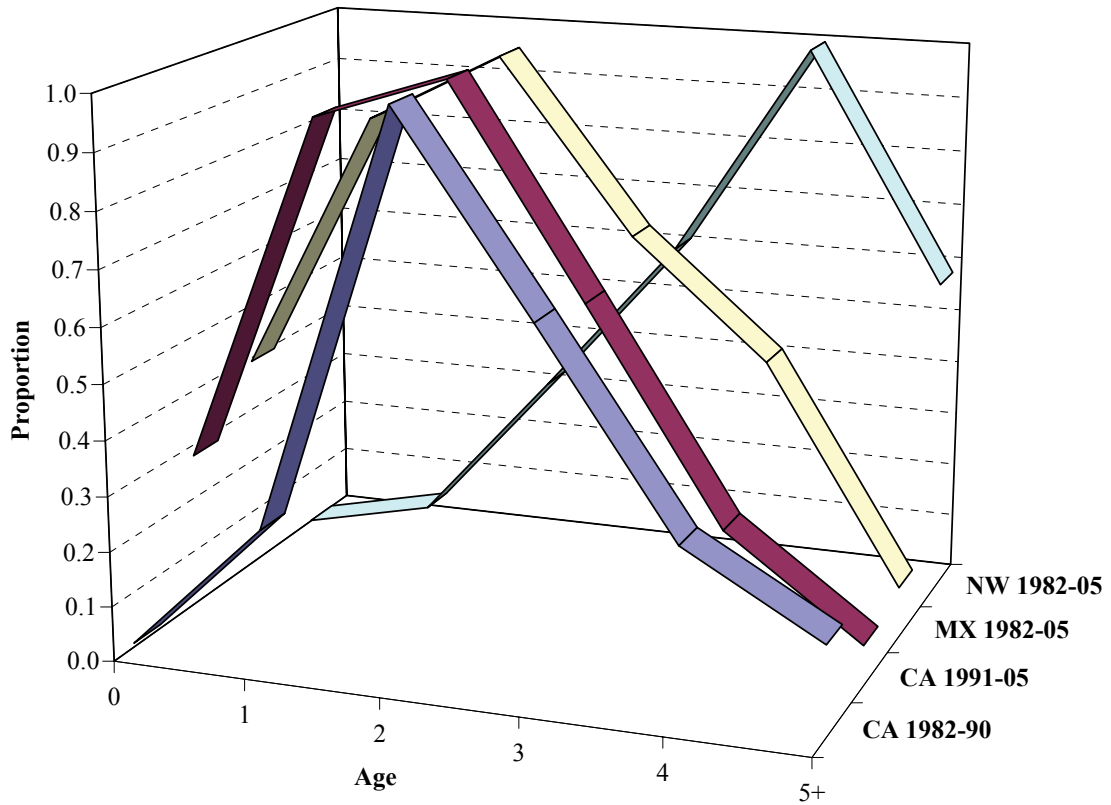


Figure 15. Estimated selectivities for the three modeled fisheries from the ASAP baseline model. The California fishery selectivity was estimated for two periods: 1982-91 (incidental fishery) and 1992-2005 (directed fishery).

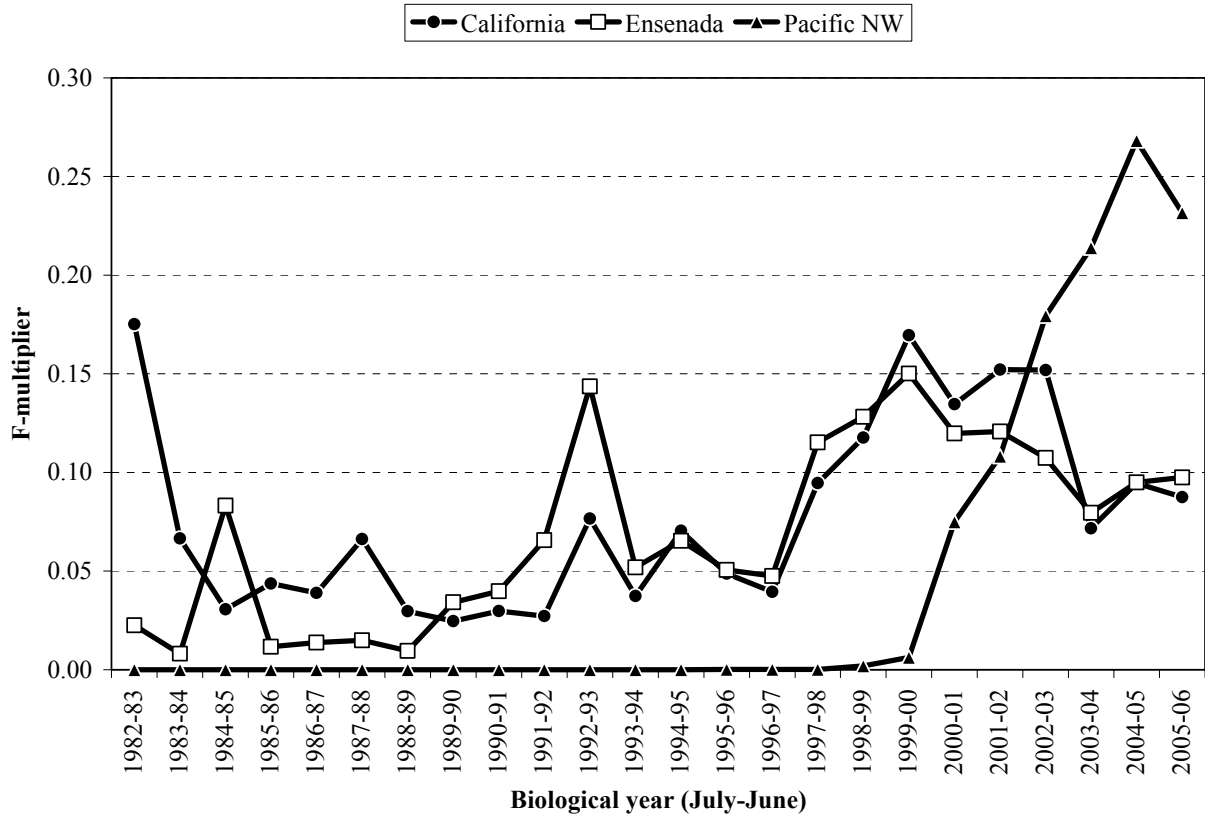


Figure 16. ASAP baseline model estimates of instantaneous rate of fishing mortality (yr^{-1}) for fully-selected age(s) in the three modeled fisheries.

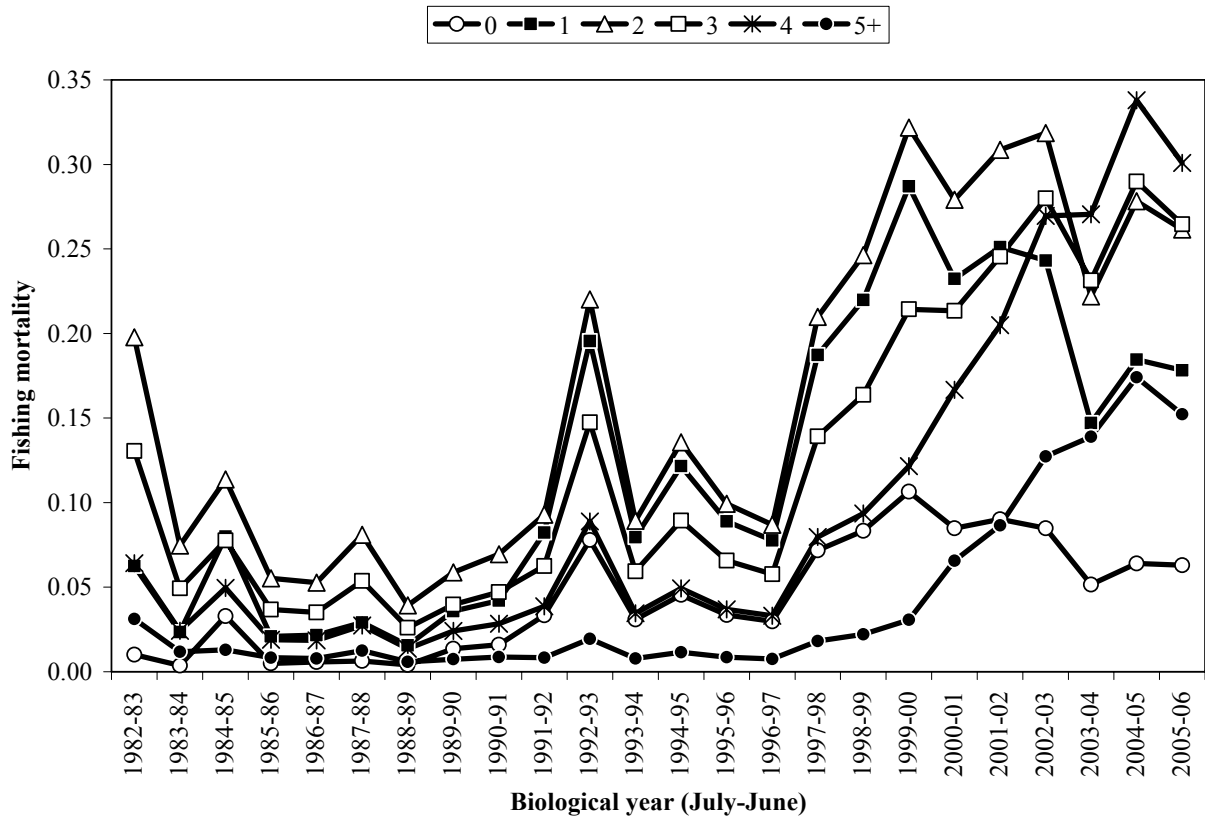


Figure 17. Estimated instantaneous rate of fishing mortality (yr^{-1}) by age and year for all fisheries combined from the ASAP baseline model.

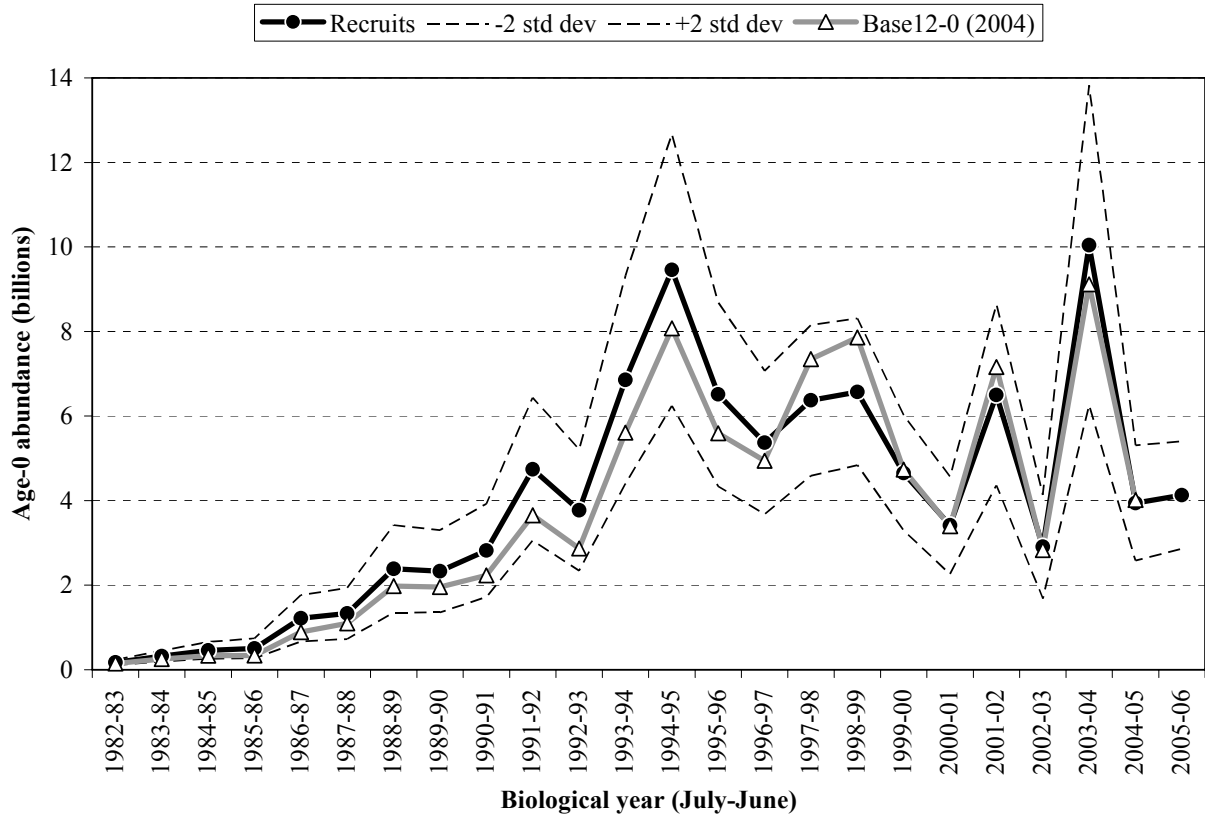


Figure 18. Pacific sardine recruitment estimates (age 0 abundance in billions) from the ASAP baseline model (solid circles) along with a 2-standard error uncertainty envelope (dashed lines). Corresponding estimates from Conser et al. (2004) are shown for comparison (triangles).

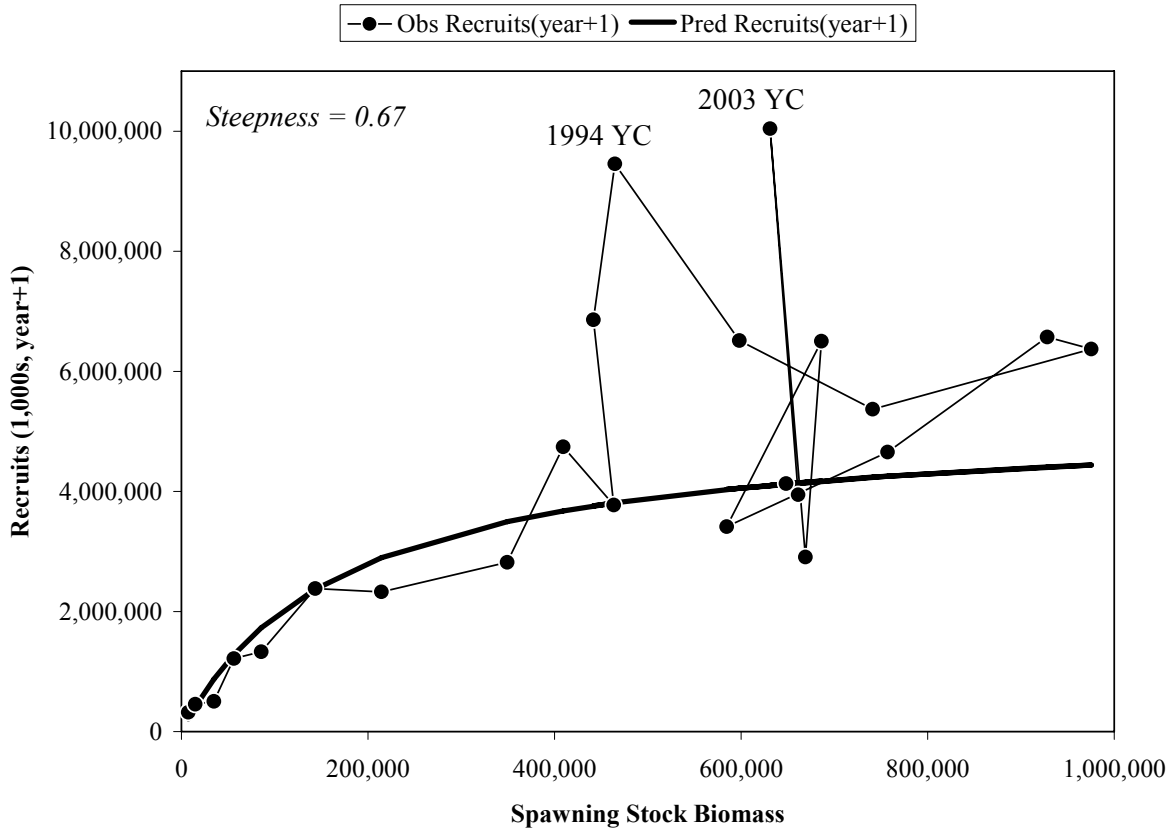


Figure 19. Sardine spawning stock biomass and recruitment estimates from the baseline model. Estimated recruitments from the Beverton-Holt stock-recruitment relationship are also shown. Year labels indicate the biological year associated with the spawning stock biomass.

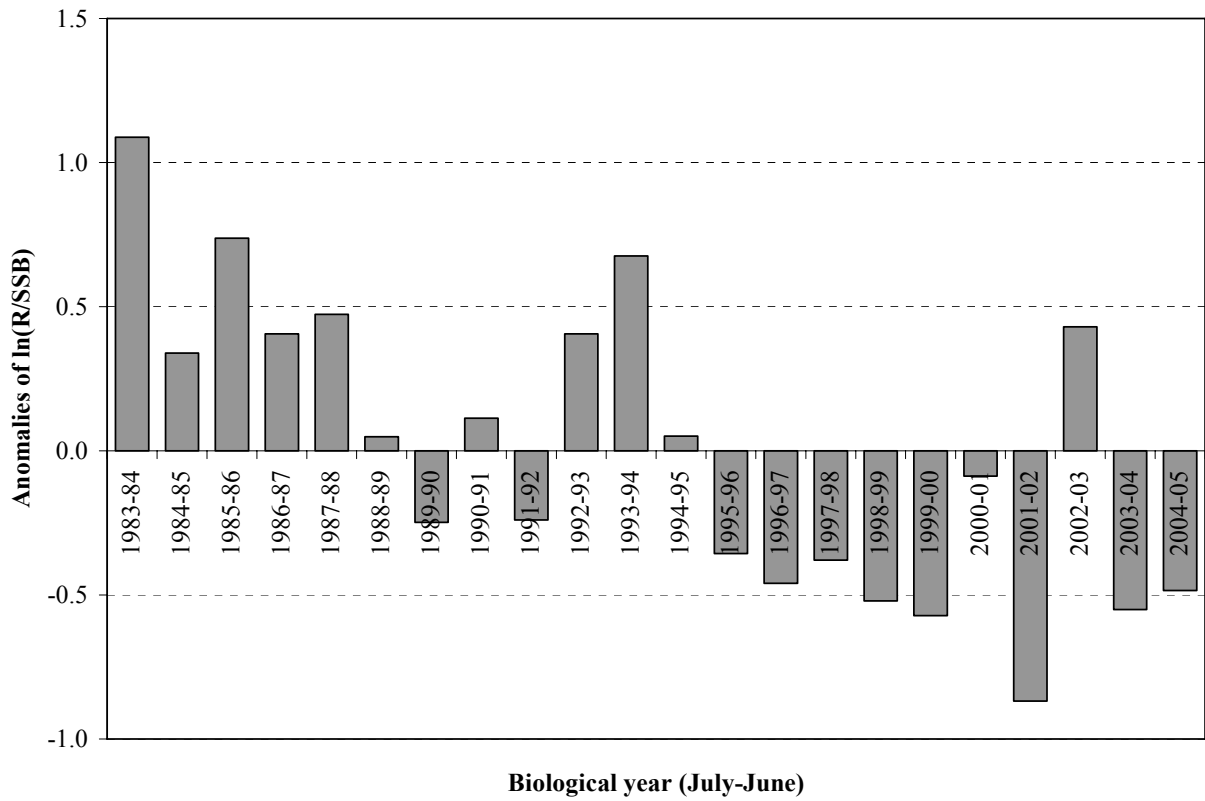


Figure 20. Relative reproductive success of Pacific sardine, 1982-83 to 2004-05.

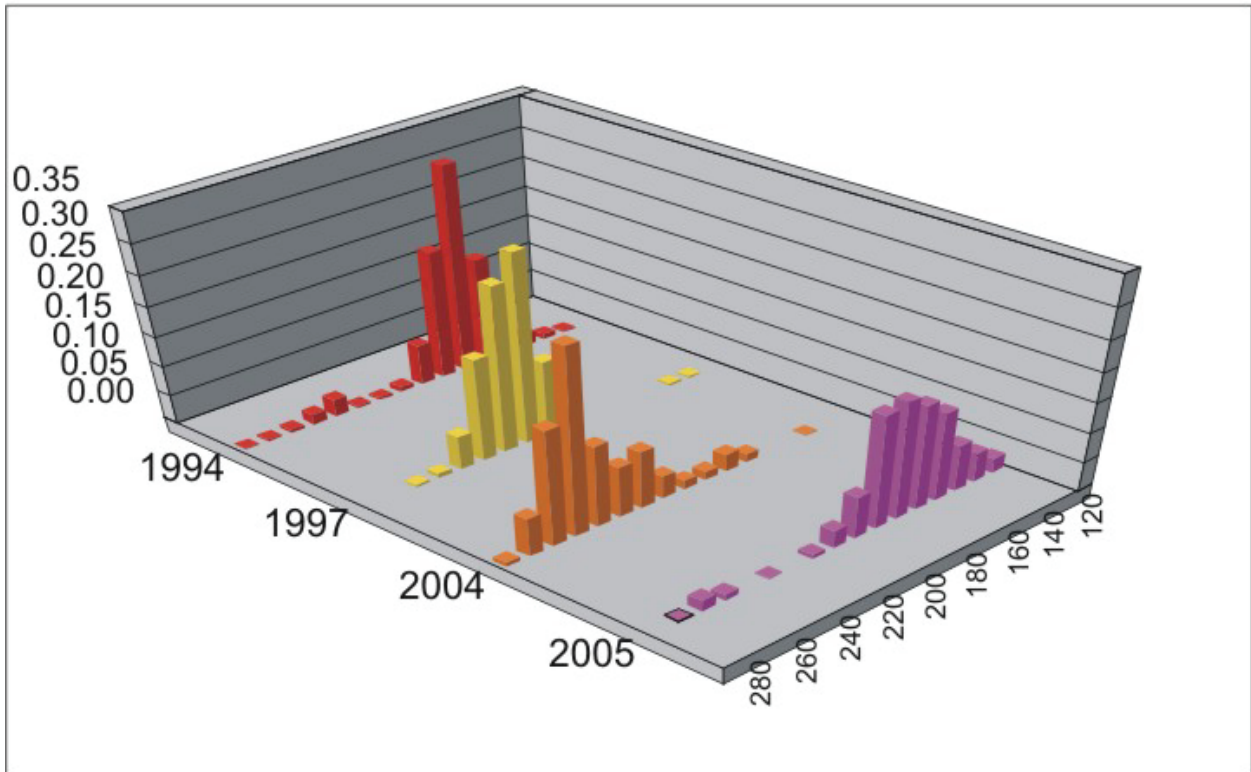
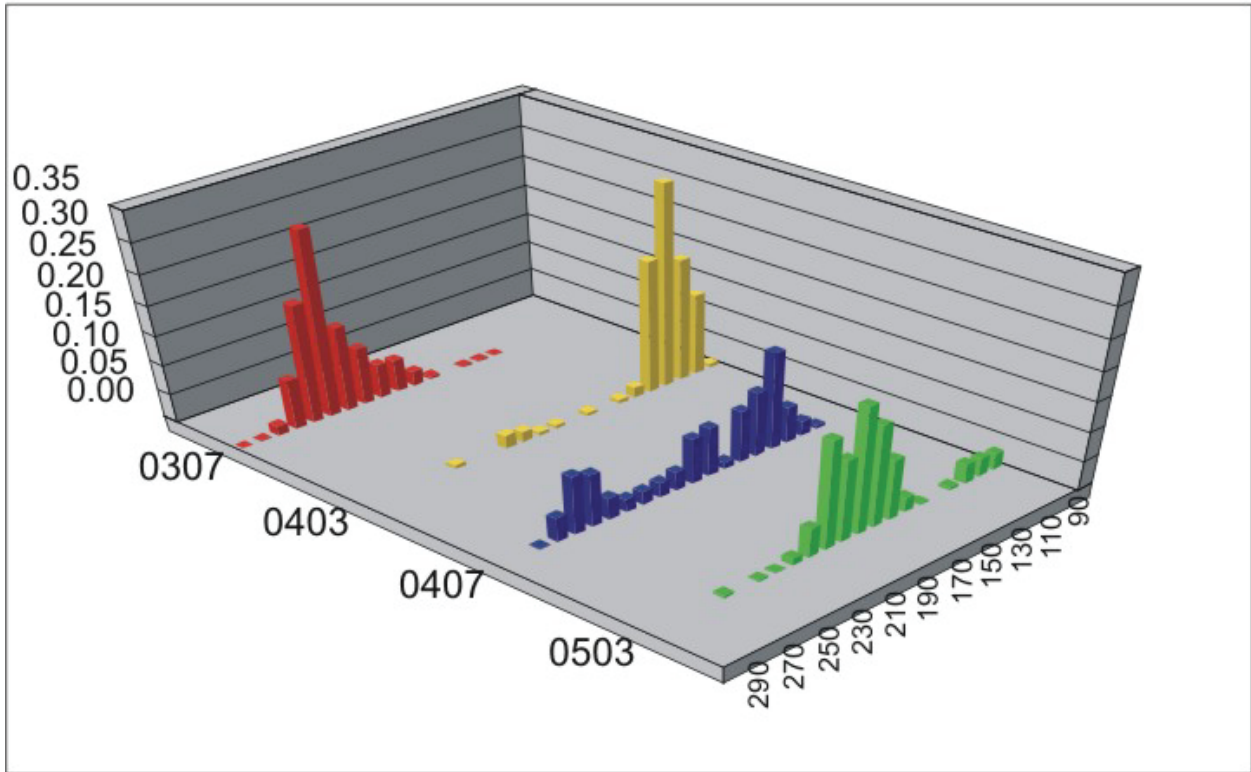


Figure 21. Length compositions of Pacific sardine collected during fishery-independent surveys, with evidence for a relatively strong 2003 year class in both areas: (top) Pacific northwest surveys in July 2003, March 2004, July 2004, and March 2005; (bottom) April surveys conducted in California offshore waters in 1994, 1997, 2004, and 2005.

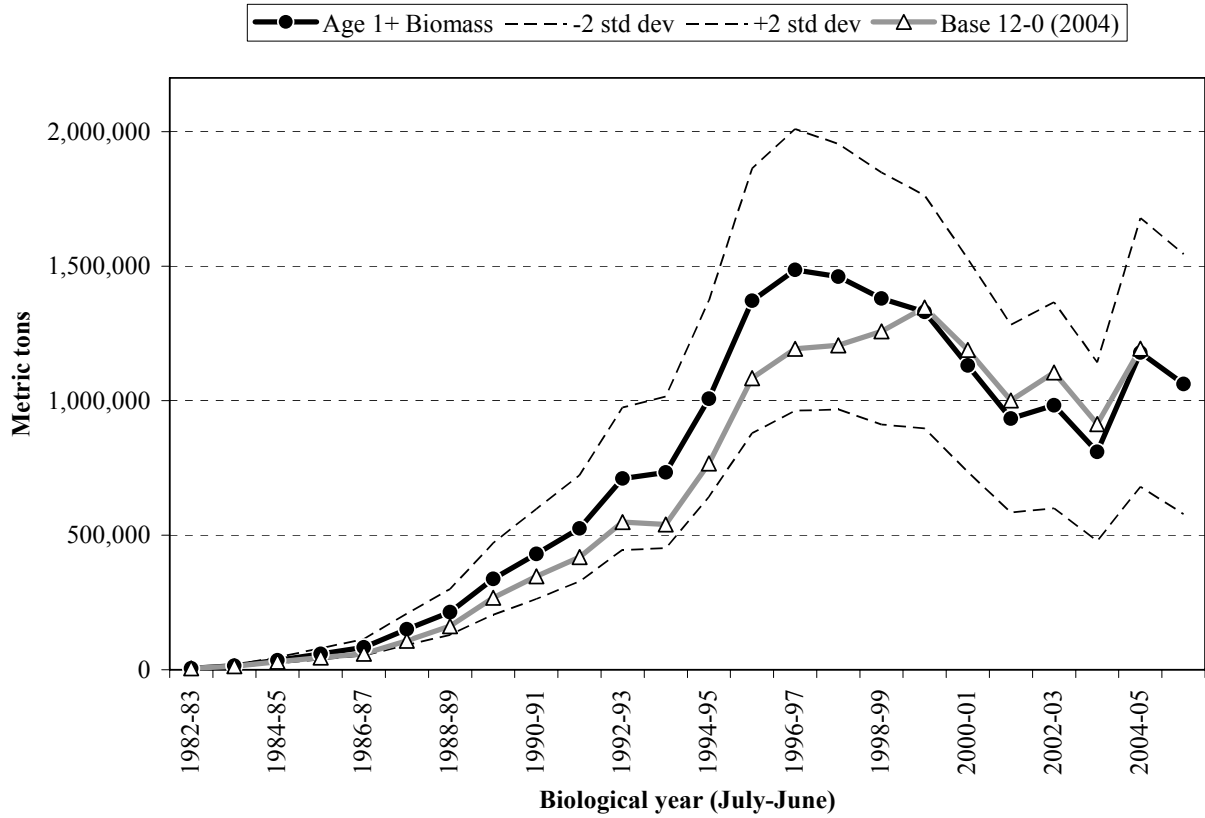


Figure 22. Pacific sardine stock (ages 1+) biomass estimates from the ASAP baseline model (solid circles) along with a 2-standard deviation uncertainty envelope (dashed lines). Corresponding estimates from Conser et al. (2004) are shown for comparison (triangles).

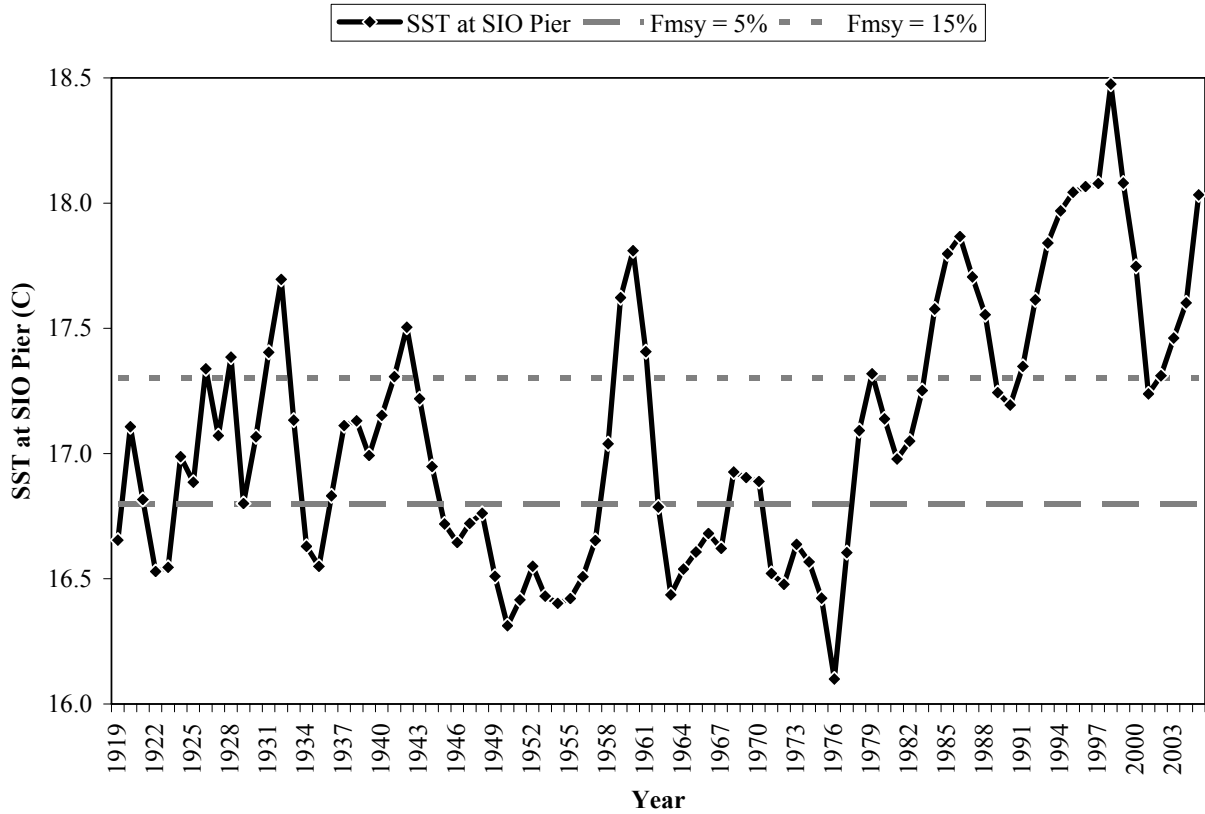


Figure 23. Three-season (July-June) running average of sea surface temperature (SST) data collected daily at Scripps Institution of Oceanography pier since 1916. For any given year, SST is the running average temperature during the three preceding years, e.g. the 2005 estimate is the average from July 1, 2002 through June 30, 2005. The 2005 value used for management in 2006 is 18.0 °C, so a 15% exploitation fraction (F_{msy}) should be applied in the harvest control rule.

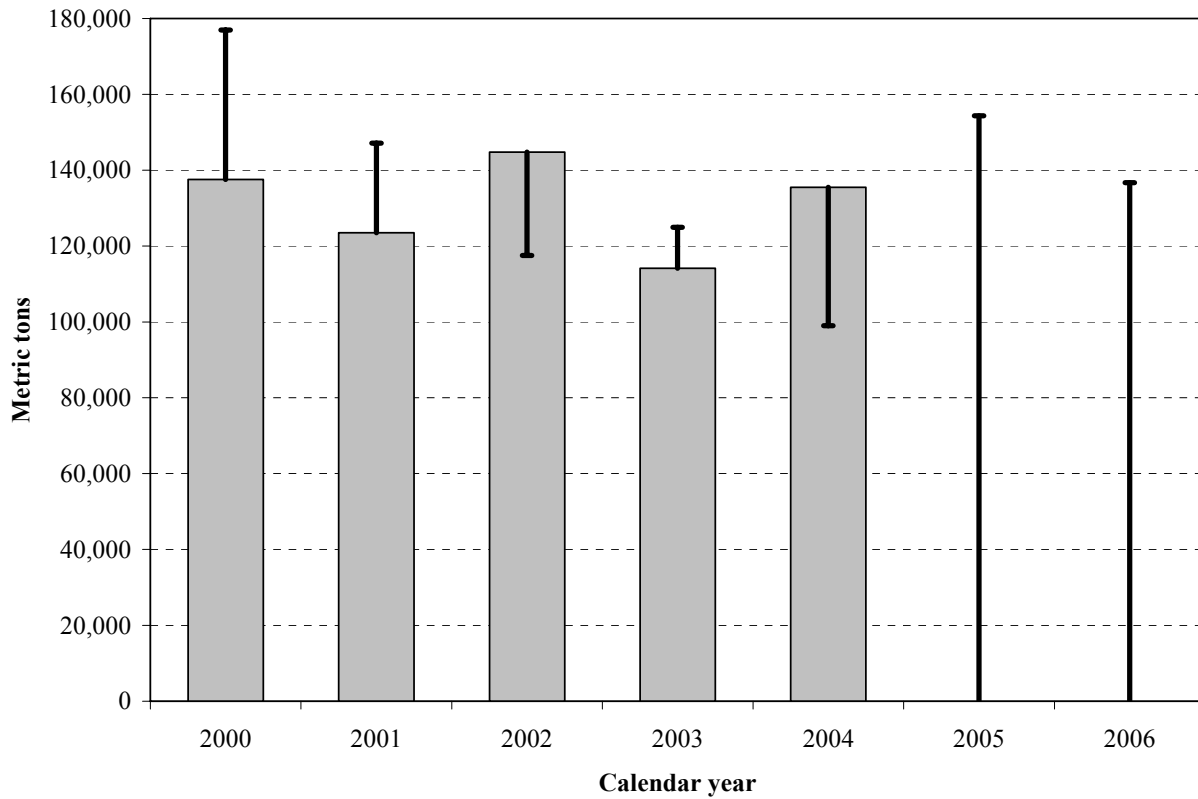


Figure 24. Coast-wide harvest of Pacific sardine relative to retrospective harvest guidelines (HGs) based on the biomass time series from the current assessment. Total HGs are based on the same formula presented in 'HARVEST GUIDELINE FOR 2006' but are not prorated for assumed U.S. Distribution and therefore represent the sustainable harvest for the west coast of North America.

APPENDIX I – Reprint of the ASAP Model Description (Legault and Restrepo. 1999)

A FLEXIBLE FORWARD AGE-STRUCTURED ASSESSMENT PROGRAM*Christopher M. Legault¹, Victor R. Restrepo²***SUMMARY**

This paper documents an age-structured assessment program (ASAP) which incorporates various modeling features that have been discussed by the SCRS in recent years, particularly during meetings of the bluefin tuna species group. The software was developed using the commercial package of AD Model Builder, an efficient tool for optimization that uses an automatic differentiation algorithm in order to find a solution quickly using derivatives calculated to within machine precision, even when the number of parameters being estimated is rather large. The model is based on forward computations assuming separability of fishing mortality into year and age components. This assumption is relaxed by allowing for fleet-specific computations and by allowing the selectivity at age to change smoothly over time. The software can also allow the catchability associated with each abundance index to vary smoothly with time. The problem's dimensions (number of ages, years, fleets and abundance indices) are defined at input and limited by hardware only. We illustrate an application of ASAP using data for western Atlantic bluefin tuna.

RÉSUMÉ

Le présent travail documente un programme d'évaluation structuré par âge (ASAP) qui comprend plusieurs facettes de modélisation qui ont été abordées par le SCRS ces dernières années, notamment pendant les sessions du groupe d'espèce thon rouge. Le logiciel a été élaboré au moyen du programme commercial AD Model Builder, qui est un outil efficace d'optimisation utilisant un algorithme différentiel automatique pour arriver rapidement à une solution au moyen de dérivatifs calculés avec une précision quasi-mécanique, même lorsque le nombre de paramètres à estimer est assez important. Le modèle se base sur des calculs forward postulant que la mortalité par pêche peut être ventilée par année et par âge. Ce postulat est rendu plus flexible par le fait qu'il prévoit la réalisation de calculs en fonction de la flottille, ainsi que l'évolution progressive dans le temps de la sélectivité par âge. Le logiciel peut aussi tenir compte de la variation graduelle dans le temps de la capturabilité associée à chaque indice de l'abondance. Les dimensions du problème (nombre d'âges, d'années, de flottilles et d'indices d'abondance) sont définies en tant que données d'entrée et ne sont limitées que par le matériel. Une application de l'ASAP à des données sur le thon rouge de l'Atlantique ouest est présentée à titre d'illustration.

RESUMEN

Este papel documenta un programa de evaluación estructurado por edad (ASAP), que incorpora varias características de modelización discutidas por el SCRS en años recientes, particularmente durante las reuniones del Grupo de especies del atún rojo. Se desarrolló el programa utilizando el paquete comercial AD Model Builder, una eficaz herramienta para la optimización, que utiliza un algoritmo de diferenciación automática para hallar una rápida solución empleando derivados calculados con precisión, incluso cuando el número de parámetros que se estima es amplio. El modelo se basa en cálculos "forward" que asumen la capacidad de separación de la mortalidad por pesca en componentes anuales y por edad. Este supuesto se suaviza permitiendo a lo largo del tiempo el cambio progresivo de los cálculos específicos de la flota y la de la selectividad por clases de edad. El programa también permite que la capturabilidad asociada a cada índice de abundancia varíe gradualmente a lo largo del tiempo. Las dimensiones del problema (números de edades, años, flotas e índices de abundancia) se definen en los datos de entrada y sólo están limitados por el hardware. Se ilustra una aplicación de ASAP que utiliza datos para el atún rojo del Atlántico oeste.

¹ U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, 75 Virginia Beach Dr., Miami, Florida 33149, USA.

² University of Miami, Rosenstiel School of Marine and Atmospheric Science, Cooperative Unit for Fisheries Education and Research, 4600 Rickenbacker Causeway, Miami, Florida 33149, USA.

Introduction

Stock assessment algorithms explain observed data through a statistical estimation procedure based on a number of assumptions. The number and severity of these assumptions are determined by the algorithm and reflect not only the user's paradigms but also the amount and quality of the available data. We present an age-structured assessment program (ASAP) which allows easy comparison of results when certain assumptions are made or relaxed. Specifically, ASAP is a flexible forward program that allows the assumption of separability of gear specific fishing mortality into year and age components to be relaxed and change over time. The assumption of constant catchability coefficients for scaling observed indices of abundance can also be relaxed to change over time. The advantage of this flexibility is an increased ability to fit models and less reliance on assumptions that are thought to be too strict. The disadvantage of such an approach is exactly this ability to explain the data in more (and possibly contradictory) ways through different choices in the amount of variability in the changing parameters. Explicit choices for relative weightings amongst the different parts of the objective function must be made. Slight changes in these parameter weightings in a complex model can produce vastly different results, while a simpler model will be more consistent (not necessarily more accurate) relative to changes in the parameter weightings.

Allowing flexibility in selectivity and catchability greatly increases the number of parameters to be estimated. We use the commercial software package AD Model Builder to estimate the relatively large number of parameters. The software package is based on a C++ library of automatic differentiation code (see Greiwank and Corliss 1991) which allows relatively fast convergence by calculating derivatives to machine precision accuracy. These derivatives are used in a quasi-Newton search routine to minimize the objective function. The array sizes for parameters are defined on input and limited only by hardware. Currently, ASAP is compiled to estimate a maximum of 5,000 parameters, but this can be increased by changing one line of code.

The AD Model Builder software package allows many matrix operations to be programmed easily in its template language and allows for the estimation of parameters to occur in phases. The phases work by estimating only some parameters initially and adding more parameters in a stepwise fashion until all parameters are estimated. When new parameters are added by incrementing the phase, the previously estimated parameters are still estimated, not fixed at the previous values. These phases also allow easy switching between simple and complex models by simply turning on or off phases through the input file. For example, index specific catchability coefficients can be allowed to change or have a constant value over time. An additional feature of the AD Model Builder software is easy likelihood profiling of specified variables, although this can be time consuming for models with large numbers of parameters. We first describe ASAP with all the features and then compare two analyses for bluefin tuna using different levels of complexity in the program.

The Model

Population dynamics

The model's population dynamics follow a standard form common to forward-projection methods such as those of Fournier and Archibald (1982), Deriso et al. (1985), Method (1998), Ianelli and Fournier (1998), and Porch and Turner (In Press). Catches and fishing mortalities can be modeled as being fleet-specific.

Let $a = \text{age}, 1 \dots A$,
 $y = \text{year}, 1 \dots Y$
 $g = \text{fleet}, 1 \dots G$
 $u = \text{abundance index series}, 1 \dots U$

Selectivity (S) at age within a year by a fleet can be limited to a range of ages and averages one, as opposed to having a maximum of one,

$$\frac{a(g_{max}) \sum_{a=1}^{a(g_{max})} S_{a,y,g} - a(g_{min})}{a(g_{max}) - a(g_{min})} + 1 = 10 \tag{1}$$

where $a(g_{min})$ and $a(g_{max})$ denote the starting and ending ages for the gear's selectivity. The output of the program makes the simple conversion from averaging one to having a maximum of one in order to simplify comparisons with other models.

Fishing mortality is modeled as the product of the selectivity at age within a year by a fleet and a year and fleet specific fishing mortality multiplier ($Fmulti_{y,g}$)

$$F_{a,y,g} = S_{a,y,g} Fmulti_{y,g} \tag{2}$$

Total fishing mortality at age and year is the sum of the fleet specific fishing mortality rates

$$F^{Tot}_{a,y} = \sum_g F_{a,y,g} \tag{3}$$

and adding the natural mortality rate (M) produces the total mortality rate

$$Z_{a,y} = F^{Tot}_{a,y} + M_{a,y} \tag{4}$$

The catch by age, year and fleet is

$$C_{a,y,g} = \frac{N_{a,y} F_{a,y,g} (1 - e^{-Z_{a,y}})}{Z_{a,y}} \tag{5}$$

where N denotes population abundance at the start of the year.

The yield by age, year and fleet is

$$Y_{a,y,g} = C_{a,y,g} W_{a,y} \tag{6}$$

where $W_{a,y}$ denotes weight of an individual fish of age a in year y .

The proportion of catch at age within a year for a fleet is

$$P_{a,y,g} = \frac{C_{a,y,g}}{\sum_a C_{a,y,g}} \quad (7)$$

The forward projections begin by computing recruitment as deviations from an average value

$$N_{1,y} = \bar{N}_1 e^{\psi_y} \quad (8)$$

where $\psi_y \sim N(0, \sigma_{\psi}^2)$ and the other numbers at age in the first year as deviations from equilibrium

$$N_{a,1} = N_{1,1} e^{\sum_{m=1}^{a-1} Z_{1,m}} e^{\psi_a} \quad \text{for } a < A$$

$$N_{a,1} = \frac{N_{1,1} e^{\sum_{m=1}^{a-1} Z_{1,m}}}{1 - e^{-Z_{a,1}}} e^{\psi_a} \quad \text{for } a = A$$

where $\psi_a \sim N(0, \sigma_{\psi}^2)$. The remaining population abundance at age and year is then computed

$$N_{a,y} = N_{a-1,y-1} e^{-Z_{a-1,y-1}} \quad \text{for } a < A$$

$$N_{a,y} = N_{a-1,y-1} e^{-Z_{a-1,y-1}} + N_{a,y-1} e^{-Z_{a,y-1}} \quad \text{for } a = A.$$

Predicted indices of abundance (\hat{I}) are a measure of the population scaled by catchability coefficients (q) and selectivity at age (S)

$$\hat{I}_{a,y} = q_{a,y} \sum_{a'=(a_{min})}^{a(a_{max})} S_{a',y} N_{a',y}^* \quad (11)$$

where $a(a_{min})$ and $a(a_{max})$ are the index specific starting and ending ages, respectively, and N^* corresponds to the population abundance in either numbers or weight at a specific time during the year. The abundance index selectivity at age can either be input or linked to a specific fleet. If the latter is chosen, the age range can be smaller than that of the fleet and the annual selectivity patterns are rescaled to equal 1.0 for a specified age (a_{sp}) such that the catchability coefficient is linked to this age

$$S_{a,y} = \frac{S_{a,y,g}}{S_{a_{sp},y,g}} \quad (12)$$

Time-varying parameters

Fleet specific selectivity and catchability patterns are allowed to vary over time in the model. Changes in selectivity occur each τ_y years through a random walk for every age in a given fleet

$$S_{a,y+\tau,y,g} = S_{a,y,g} e^{\epsilon_{a,y,g}} \quad (13)$$

where $\epsilon_{a,y,g} \sim N(0, \sigma_{\epsilon}^2)$ and are then rescaled to average one following equation (1). If τ_y is greater than one, then the selectivity at age for the fleet is the same as previous values until τ_y years elapse. The catchability coefficients also follow a random walk

$$q_{a,y+1} = q_{a,y} e^{\omega_{a,y}} \quad (14)$$

as do the fleet specific fishing mortality rate multipliers

$$F_{mult,y+1,g} = F_{mult,y,g} e^{\delta_{a,y}} \quad (15)$$

where $\omega_{a,y} \sim N(0, \sigma_{\omega}^2)$ and $\delta_{a,y} \sim N(0, \sigma_{\delta}^2)$.

Parameter estimation

The number of parameters estimated depends upon the values of τ_y and whether or not changes in selectivity or catchability are considered. When time varying selectivity and catchability are not considered the following parameters are estimated: Y recruits, $A-1$ population abundance in first year, Y/G fishing mortality rate multipliers, AG selectivities (if all ages selected by all gears), U catchabilities, and Z stock recruitment parameters. Inclusion of time varying selectivity and catchability can increase the number of parameters to be estimated by a maximum of $(Y-1)AG + (Y-1)U$. Sensitivity analyses can be conducted to determine the tradeoffs between number of parameters estimated and goodness of fit caused by changes in the τ_y values.

The likelihood function to be minimized includes the following components (ignoring constants): total catch in weight by fleet (lognormally distributed)

$$L_1 = \lambda_1 [\ln(\sum_a Y_{a,y,g}) - \ln(\sum_a \hat{Y}_{a,y,g})]^2; \quad (16)$$

catch proportions in numbers of fish by fleet (multinomially distributed)

$$L_2 = -\sum_y \sum_g \lambda_{2,y,g} \sum_a P_{a,y,g} \ln(\hat{P}_{a,y,g}) - P_{a,y,g} \ln(P_{a,y,g}); \quad (17)$$

and indices of abundance (lognormally distributed)

$$L_3 = \sum_a \lambda_{3,g} \sum_y [\ln(\hat{I}_{y,g}) - \ln(\hat{I}_{y,g}^*)]^2 / 2\sigma_{y,g}^2 + \ln(\sigma_{y,g}), \quad (18)$$

where variables with a hat are estimated by the model and variables without a hat are input as observations. The second term in the catch proportion summation causes the likelihood to equal zero for a perfect fit. The sigmas in equation 18 are input by the user and can optionally be set to all equal 1.0 for equal weighting of all index points. The weights (λ) assigned to each component of the likelihood function correspond to the inverse of the variance assumed to be associated with that component. Note that the year and fleet subscripts for the catch proportion lambdas allow zero weights to be assigned to specific year and fleet combinations such that only the total catch in weight by that fleet and year would be incorporated in the objective function. Priors for the

variances of the time varying parameters are also included in the likelihood by setting λ equal to the inverse of the assumed variance for each component

$$\begin{aligned}
 L_4 &= \sum_g \lambda_{4,g} \sum_a \sum_y \varepsilon_{a,y,g}^2 && \text{(selectivity)} && (19) \\
 L_5 &= \sum_a \lambda_{5,a} \sum_y \omega_{a,y}^2 && \text{(catchability)} && (20) \\
 L_6 &= \sum_g \lambda_{6,g} \sum_y \eta_{y,g}^2 && \text{(F multipliers)} && (21) \\
 L_7 &= \lambda_7 \sum_y v_y^2 && \text{(recruitment)} && (22) \\
 L_8 &= \lambda_8 \sum_y \psi_y^2 && \text{(N year 1)} && (23)
 \end{aligned}$$

Additionally, there is a prior for fitting a Beverton and Hoit type stock-recruitment relationship

$$L_9 = \lambda_9 \sum_y \left[\ln(N_{1,y}) - \ln \left(\frac{\alpha SSB_{y-1}}{\beta + SSB_{y-1}} \right) \right]^2 \tag{24}$$

where SSB denotes the spawning stock biomass and α and β are parameters to be estimated. Penalties are used to determine the amount of curvature allowed in the fleet selectivity patterns, both at age

$$A_1 = \lambda_{p1} \sum_y \sum_g \sum_a \frac{\alpha(\varepsilon_{a,y,g})^2}{\sigma(\varepsilon_{a,y,g})} (S_{a,y,g} - 2S_{a,y-1,g} + S_{a,y+2,g})^2 \tag{25}$$

and over time

$$\rho_2 = \lambda_{p2} \sum_a \sum_g \sum_y \sum_{j=1}^{y-2} (S_{a,y,g} - 2S_{a,y-1,g} + S_{a,y+2,g})^2 \tag{26}$$

The function to be minimized is then the sum of the likelihoods and penalties

$$L = L_1 + L_2 + L_3 + L_4 + L_5 + L_6 + L_7 + L_8 + L_9 + A_1 + \rho_2 \tag{27}$$

An additional penalty is utilized in early phases of the minimization to keep the average total fishing mortality rate close to the natural mortality rate. This penalty ensures the population abundance estimates do not get exceedingly large during early phases of the minimization. The final penalty added to the objective function forces the parameters for fleet selectivities in the first year to average 1.0. This penalty prevents multiple parameter sets from having the same objective function value, which would cause difficulty for the minimization routine. Each component of the objective function is reported in the output file along with the corresponding number of observations, weight assigned to that component, and residual sum of squared deviations (if appropriate).

Additional Features

The model optionally does some additional computations once the likelihood function has been minimized. These "extras" do not impact the solution, they are merely provided for reference. Each fleet can be designated as either directed or nondirected for the projections and F reference point calculations, with the option to modify the nondirected F in the future. The directed fleets are combined to form an overall selectivity pattern that is used to solve for common fishing mortality rate reference points ($F_{0.1}$, F_{max} , $F_{30\%SPR}$, $F_{40\%SPR}$ and F_{msy}) and compared to the terminal year F estimate. The inverse of the SPR for each of these points is also given so replacement lines corresponding to these reference values can be plotted on the spawner-recruit relationship. Projections are computed using either the stock-recruitment relationship or input values to generate future recruitment. The projections for each successive year can be made using either a total catch in weight or the application of a static F_{XSSB} , where X is input. A reference year is also input that allows comparison of the spawning stock biomass (SSB) in the terminal year and that in the final projection year as SSB_{y-1}/SSB_{ref} . Likelihood profiles for these SSB ratios can optionally be generated.

Example: Western Atlantic Bluefin Tuna

Two analyses of western Atlantic bluefin tuna data using ASAP are presented here. The first analysis (simple) did not allow selectivity and catchability to change over time (225 parameters estimated). The second analysis (complex) used the full complexity allowed by the model, with fleet selectivities allowed to change every two years and index catchabilities allowed to change every year (914 parameters estimated). In both analyses the model was structured for years 1970-1995, ages 1-10+, five fleets, and seven tuning indices (each point input with a variance) with all likelihood component weightings equal between the analyses. The natural mortality rate was set at 0.14 for all ages (for data details see Restrepo and Legault In Press). The number of observations associated with, and the weights given to, each part of the likelihood function are shown in Table 1. In this example, the weights assigned to each component were chosen arbitrarily. In an actual assessment, these weights will need to be selected by the assessment working group.

The overall fit of the complex analysis was better than the simple analysis (lower objective function value) as expected due to the greater number of parameters (Table 1). The complex analysis fits the indices better than the simple analysis, especially the US Rod and Reel Large, US Longline Gulf of Mexico, and the Japan Longline Gulf of Mexico indices (Figure 1). Recruitment estimates from the two analyses are similar to the estimates from the 1996 SCRS assessment, which used virtual population analysis (VPA) with the main differences occurring in the early years of the time series (Figure 2). The estimates of spawning stock biomass (SSB) differ between the analyses, the complex one is similar in magnitude to the SCRS96 results, while the simple analysis estimates larger values (Figure 3). However, standardizing the SSB trends (dividing by the SSB in 1975) produces similar trends for all three analyses (Figure 3). The resulting stock-recruitment relationship is shown in figure 4. The total fishing mortality rates by year and age

differ in both magnitude and pattern, with the complex analysis more closely matching the 1996 SCRS assessment (Figure 5). These differences in F are due to the assumptions about selectivity, fixed for the simple analysis and allowed to vary for the complex one (Figure 6). Note in particular the large change in selectivity of the purse seine fleet, mainly young fish in the early years and old fish in recent years. The catchability values also reflect the difference in assumptions, constant for the simple analysis and allowed to vary in the complex analysis (Figure 7). Note the large lambda given to the larval index causes the catchability coefficients to vary only slightly in the complex analysis. The catch at age proportions are fit relatively well in both analyses, the input and effective sample sizes are similar, even though this is the largest part of the total likelihood. The estimated effective sample size can be computed as

$$Effective N_g = \frac{\sum_a \sum_y \hat{p}_{a,y,g} (1 - \hat{p}_{a,y,g})^2}{\sum_a \sum_y (\hat{p}_{a,y,g} - \bar{p}_{a,y,g})^2} \quad (28)$$

(for details see McAllister and Ianelli, 1997 Appendix 2).

Discussion

The flexibility afforded by ASAP is a continuation of the trend in stock assessment programs from the relatively simple structure of Fournier and Archibald (1982) to the more flexible structure found in Methot (1998), Ianelli and Fournier (1998), and Porch and Turner (in Press). In fact, ASAP is based on the same logic as these more flexible programs, but combines the advantages of the AD Model Builder software with the more general input flexibility of stock synthesis and CATCHEM. J. Ianelli (NMFS, Seattle, pers. comm.) also provided guidance in the formulation of certain model components, specifically the logic of linking fleet specific indices with a specific age in the tuning process (see equation 12). The distinguishing feature between this approach and that found in virtual population analysis (VPA) (Gavaris 1988, Powers and Restrepo 1992) is that VPA assumes the catch at age is measured without error, while ASAP assumes the observed catch at age varies about its true value.

The flexibility of ASAP can also cause problems however. Slight changes in the weights assigned to each likelihood component can produce different results, both in magnitude and trend. The large number of parameters, in the complex model especially, required the solutions in each phase to progress towards a satisfactory region in the solution space. If any phase led the solution away from this region, the final result will not be believable (e.g. total $F < 1e-5$). This problem was not found in multiple tests using simulated data that did not contain errors or only small observation errors. Thus, the ability to fit highly complex models depends upon the quality of the data available, especially the consistency between the catch at age and the tuning indices. Nevertheless, the flexible nature of ASAP allows for easy exploration of the data to determine what level of complexity can appropriately be modeled.

Acknowledgments

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Table 1. Likelihood function components for two ASAP analyses. nobs=number of observations in that component, λ =weight given to that component, RSS=residual sum of squared deviations, L=likelihood value

Component	nobs	λ	simple		Complex	
			RSS	L	RSS	L
Catch at Age Proportions						
Total Catch in Weight	25	100.5	0.0005	0.0479	0.0001	0.0147
Rod and Reel	26	100.5	0.0015	0.1558	0.0003	0.0322
Japan Longline	26	100.5	0.0001	0.0069	0.0002	0.0070
Other Longline	26	100.5	0.0002	0.0183	0.0039	0.3913
Furze Seine	26	100.5	0.0001	0.0065	0.0000	0.0026
Other	130	100.5	0.0023	0.2353	0.0045	0.4477
Total	1300	N/A	N/A	874.10	N/A	396.47
Index Fits						
Larval Index	16	1	5.26	11.95	5.29	11.61
US Rod and Reel Small	15	1	3.95	9.33	2.02	-1.02
Canadian Tended Line	15	1	2.08	3.05	0.64	-5.95
US Rod and Reel Large	13	1	1.76	1.22	0.39	-5.74
US Longline Gulf of Mexico	9	1	6.13	15.26	0.31	-3.79
Japan Longline Gulf of Mexico	8	1	0.74	1.10	0.58	1.05
Japan Longline NW Atlantic	20	1	3.22	9.51	0.58	-9.19
Total	96	7	23.15	51.43	9.80	-13.02
Selectivity Deviations						
Rod and Reel	12	0.1	0	0	2.52	0.25
Japan Longline	12	0.1	0	0	4.42	0.44
Other Longline	12	0.1	0	0	3.56	0.36
Furze Seine	12	0.1	0	0	8.74	0.97
Other	12	0.1	0	0	3.00	0.30
Total	60	0.5	0	0	22.25	2.22
Catchability Deviations						
Larval Index	16	1000	0	0	0.00	0.29
US Rod and Reel Small	15	6.7	0	0	0.51	3.43
Canadian Tended Line	15	6.7	0	0	0.37	2.45
US Rod and Reel Large	13	6.7	0	0	0.18	1.20
US Longline Gulf of Mexico	9	6.7	0	0	0.21	1.39
Japan Longline Gulf of Mexico	8	6.7	0	0	0.00	0.03
Japan Longline NW Atlantic	20	6.7	0	0	0.35	2.35
Total	96	1040.2	0	0	1.62	11.14
Fault Deviations						
Rod and Reel	25	0.1	5.26	0.53	5.01	0.50
Japan Longline	25	0.1	21.44	2.14	19.67	1.97
Other Longline	25	0.1	24.30	2.43	23.97	2.40
Furze Seine	25	0.1	5.24	0.52	8.07	0.81
Other	25	0.1	5.60	0.56	6.84	0.68
Total	125	0.1	61.84	6.18	63.56	6.36
Recruitment	25	0.01	10.14	0.10	14.51	0.15
N in Year 1	9	1.44	3.34	4.82	3.08	4.43
Stock-Recruit Fit	25	0.001	5.47	0.01	3.94	0.00
Selectivity Curvature over Age	40	1.44	12.03	17.32	17.19	24.76
Selectivity Curvature over Time	1200	1.44	0	0	52.03	74.92
F Penalty	260	0.001	3.0E-01	2.3E-02	2.3E-02	2.3E-02
Mean Sel Year 1 Penalty	50	1	4.5E-12	4.7E-12	4.7E-12	4.7E-12
Objective Function Value				954.50		507.97

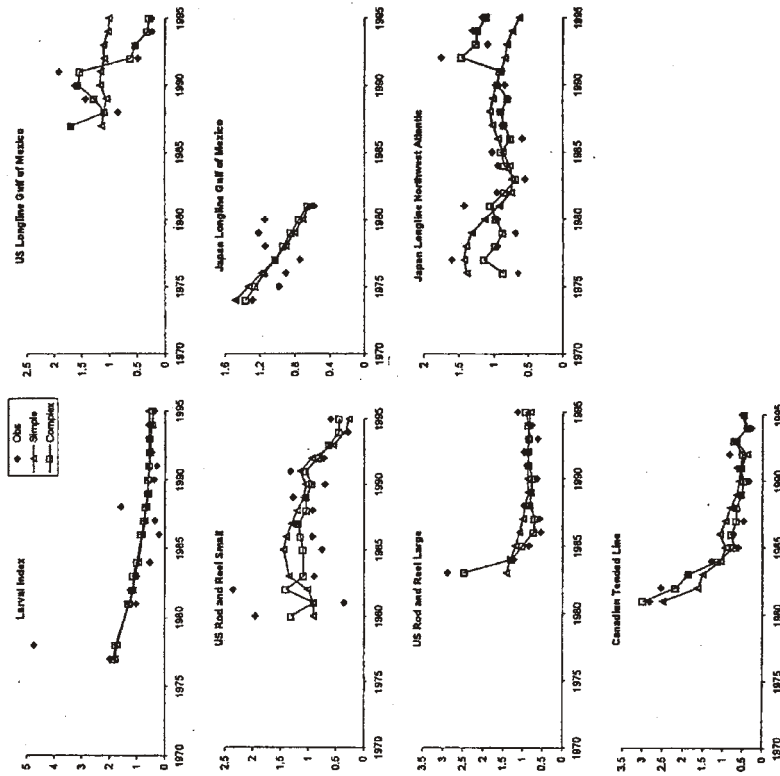


Figure 1. Observed and predicted indices for the simple and complex ASAP analyses.

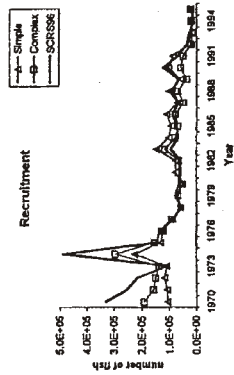


Figure 2. Estimated recruitment from two ASAP analyses and the SCRS 1996 assessment.

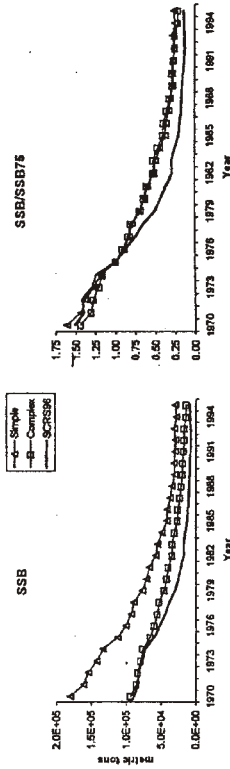


Figure 3. Spawning stock biomass (SSB) from two ASAP analyses and SCRS 1996.

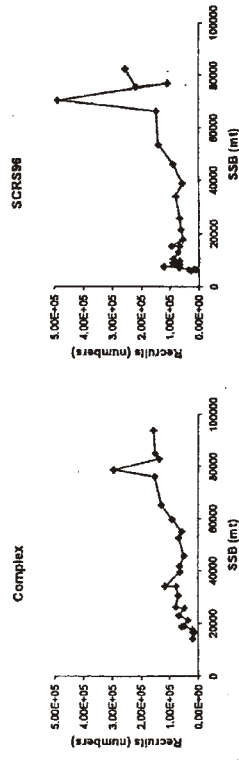


Figure 4. Complex ASAP analysis and SCRS 1996 stock-recruitment relationships.

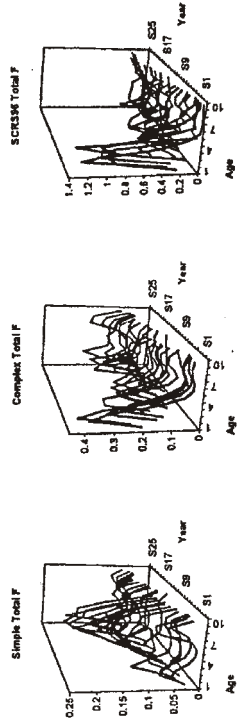


Figure 5. Estimated fishing mortality rates by age and year for two ASAP analyses and SCRS 1996.

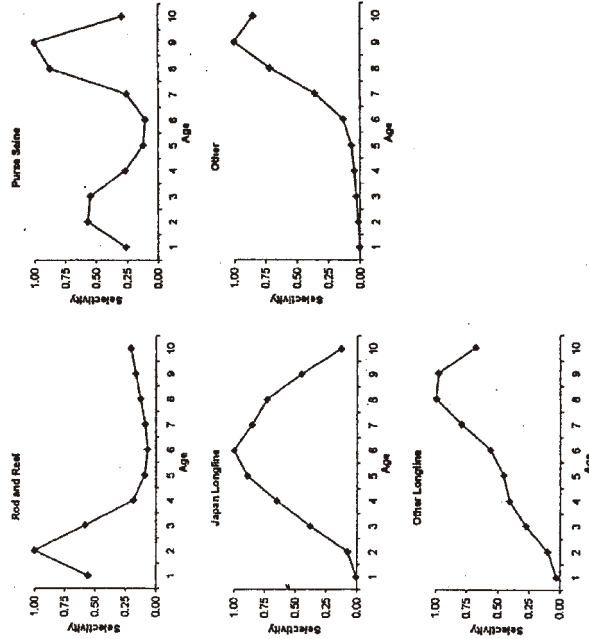


Figure 6a. Selectivity at age for the simple ASAP analysis, constant over all years for each fleet.

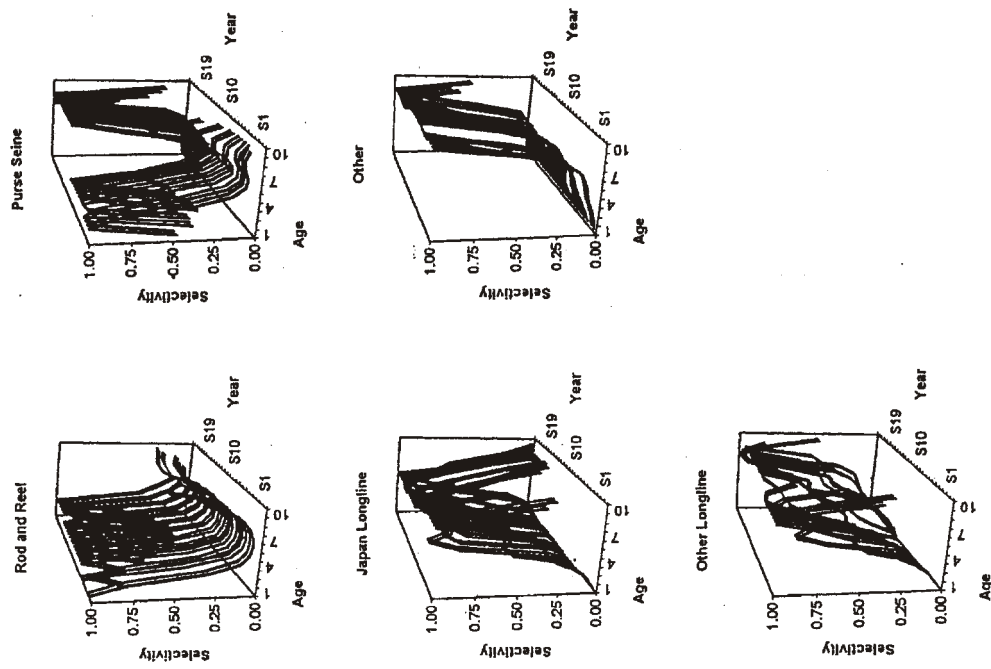


Figure 6b. Selectivity at age for the complex ASAP analysis.

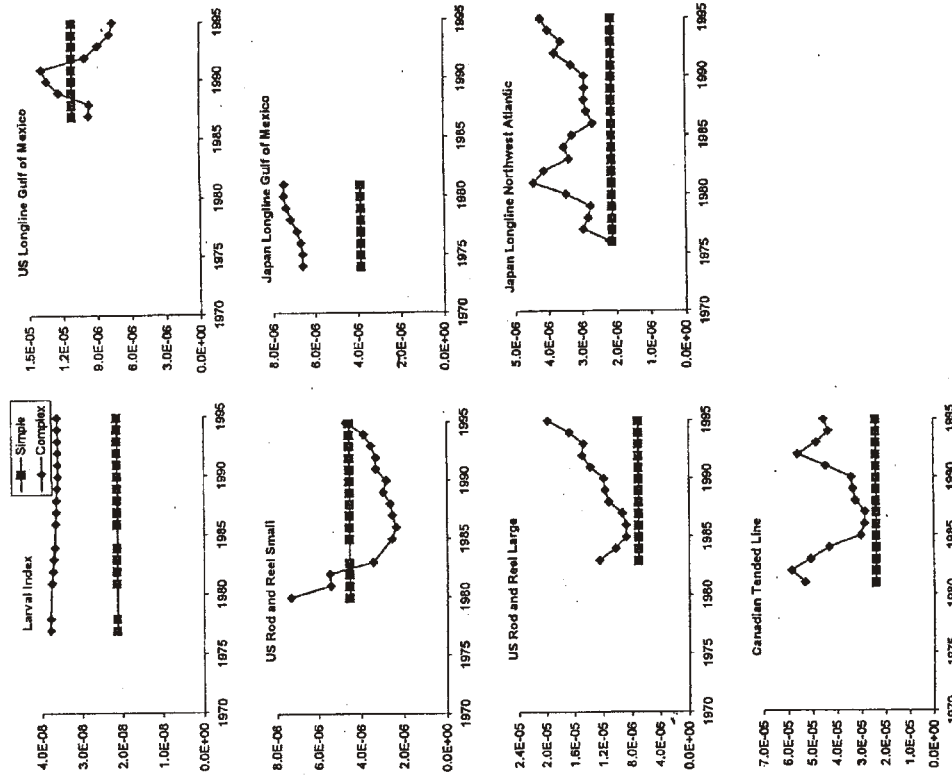


Figure 7. Catchability for each tuning index from the two ASAP analyses.

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